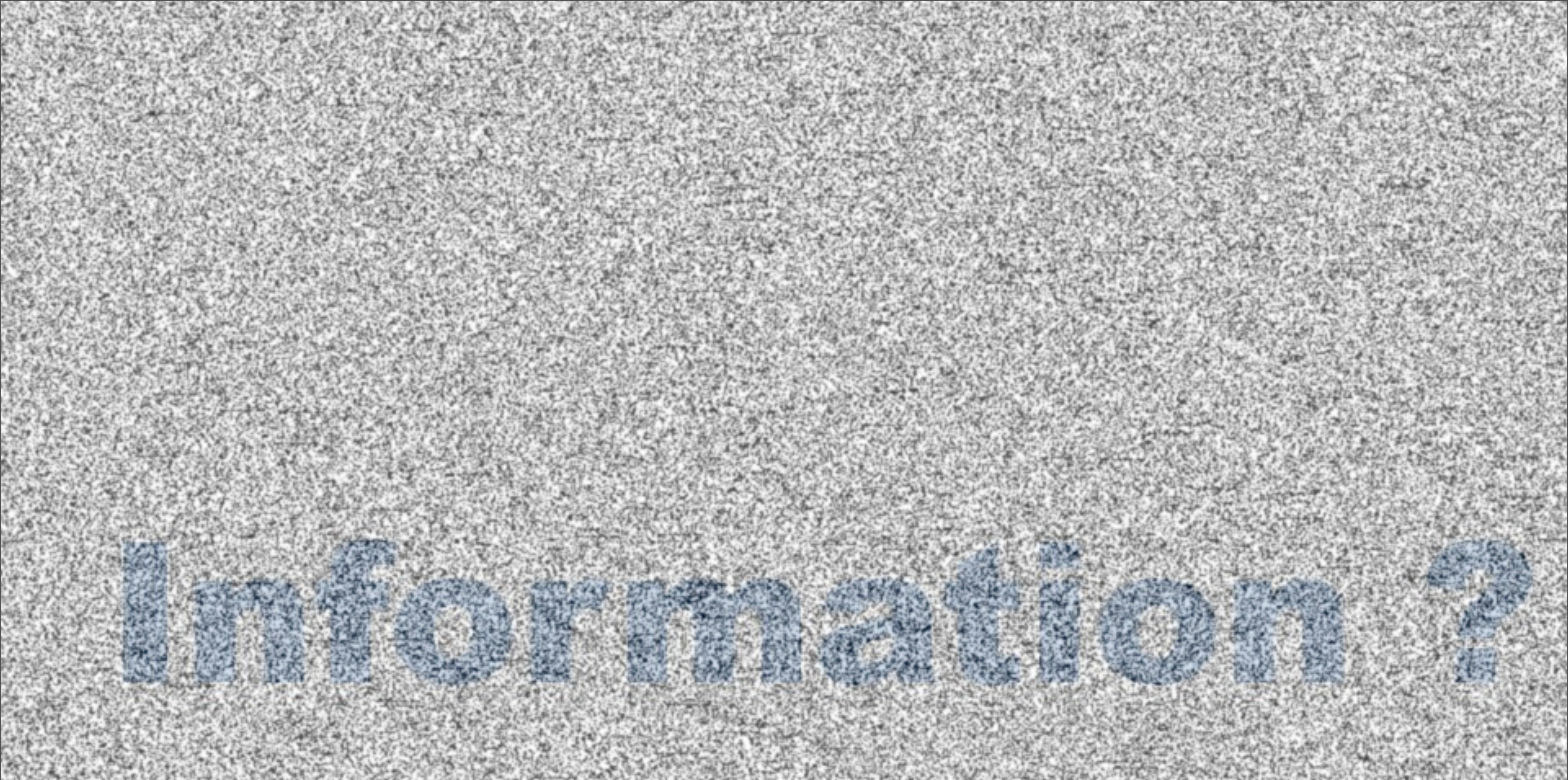
Noise Correlations



Proposal:

E. Altman, E. Demler & M. Lukin PRA (2004)

A. Polkovnikov et al., PNAS (2006)

Experiment:

Fölling et al., Nature (2005),

Greiner et al., PRL (2005)

Rom et al., Nature (2006)

Guarrera et al., PRL (2008)

related work:

Bach & Rzazewski, PRA (2004)

Z. Hadzibabic et al. PRL (2004),

Yasuda & Shimizu, PRL (1996),

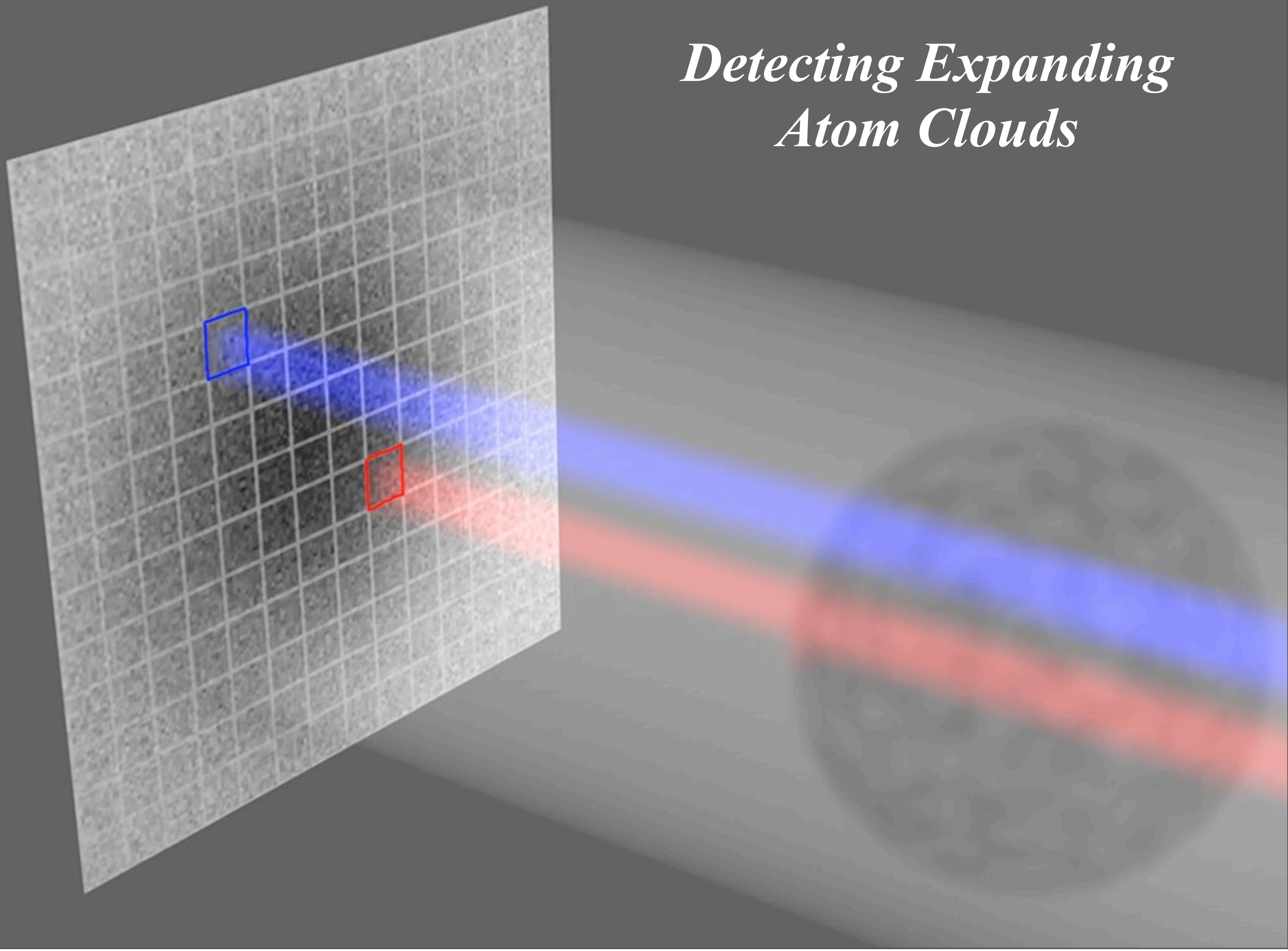
Schellekens et al., Science (2005),

Jeltes et al.,Nature (2007)

Öttl et al., PRL (2005),

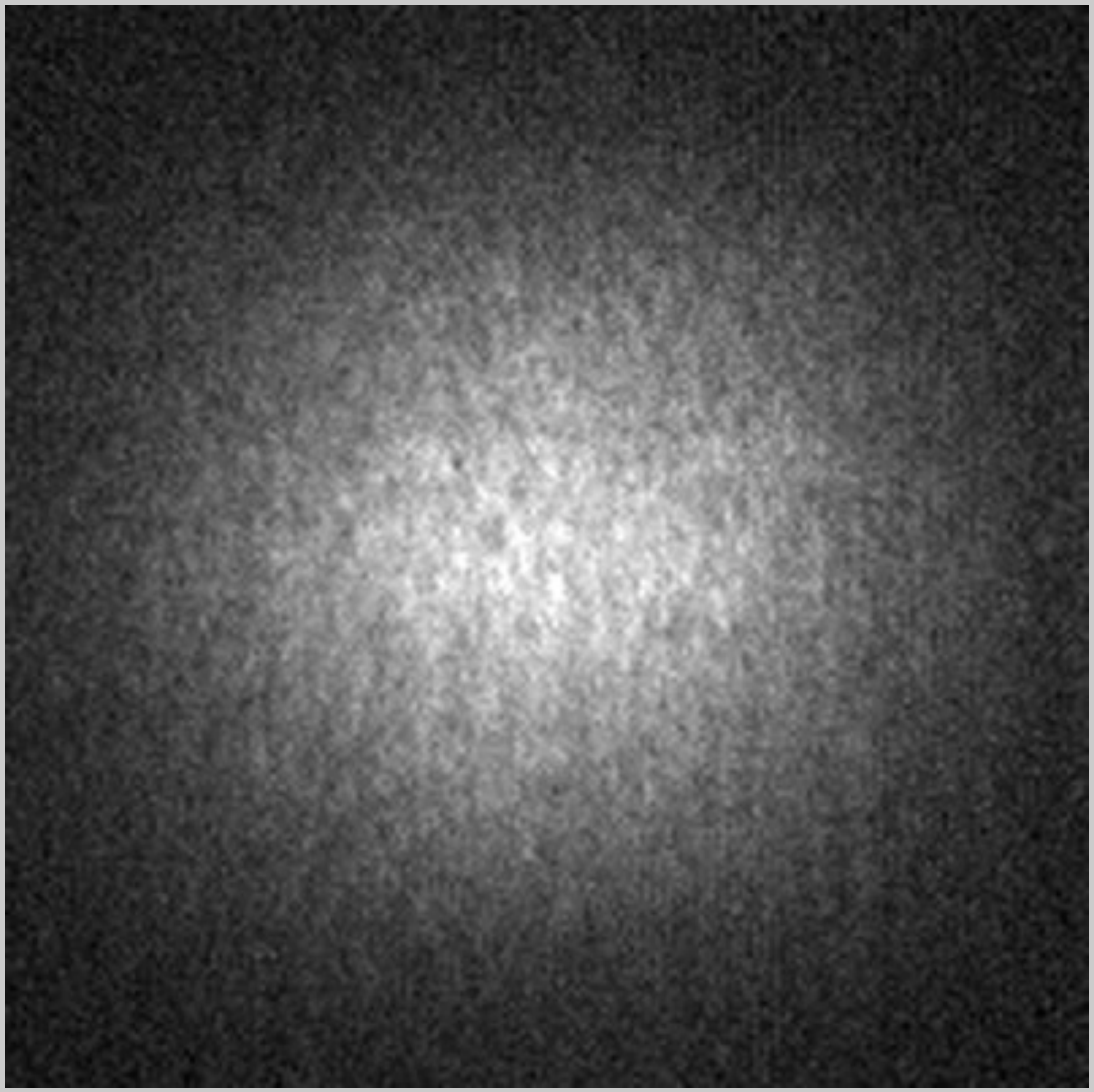
Estève et al., PRL (2006),

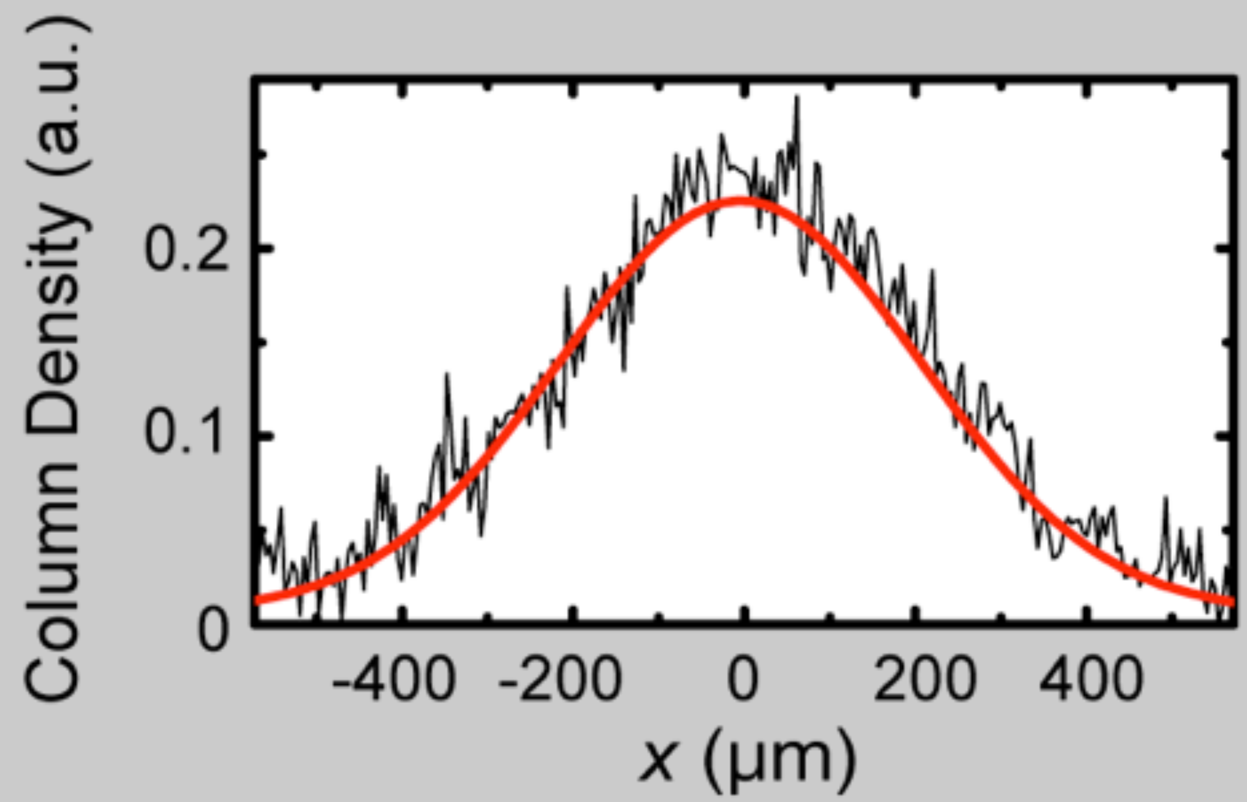
Detecting Expanding Atom Clouds



Typically Noise in Images of a Mott Insulator

Single Image

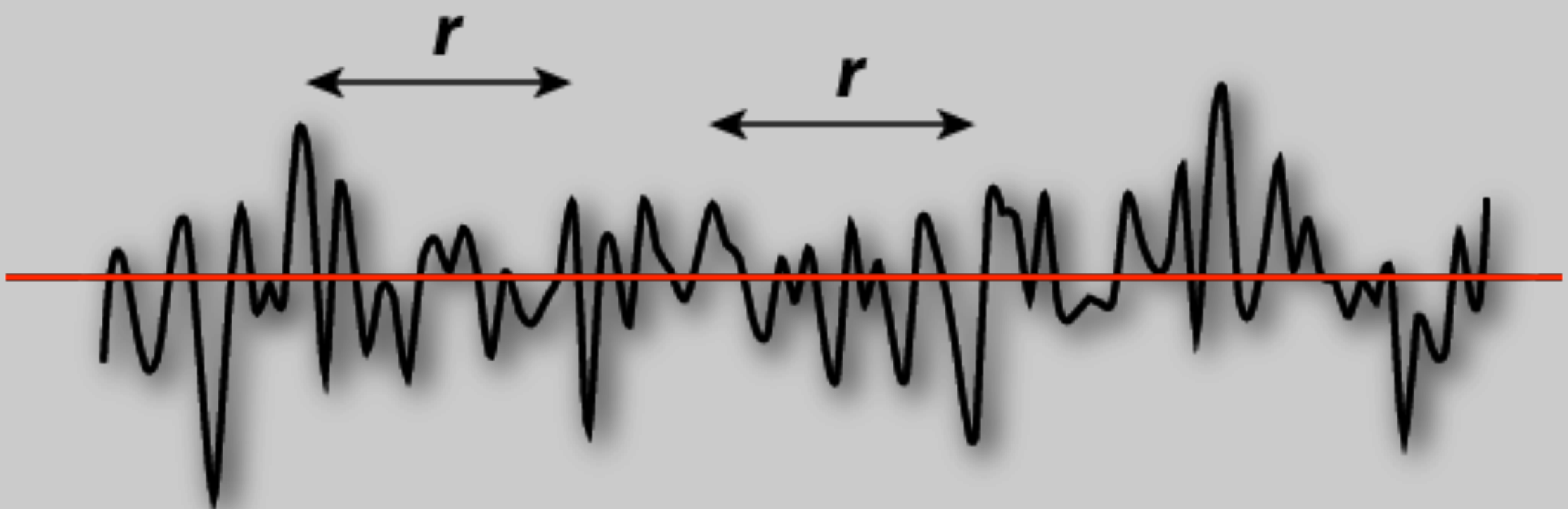




Fluctuations due to Atomic Shot Noise

$$\sigma \sim \sqrt{N_{bin}}$$

Corrleations in Noise?

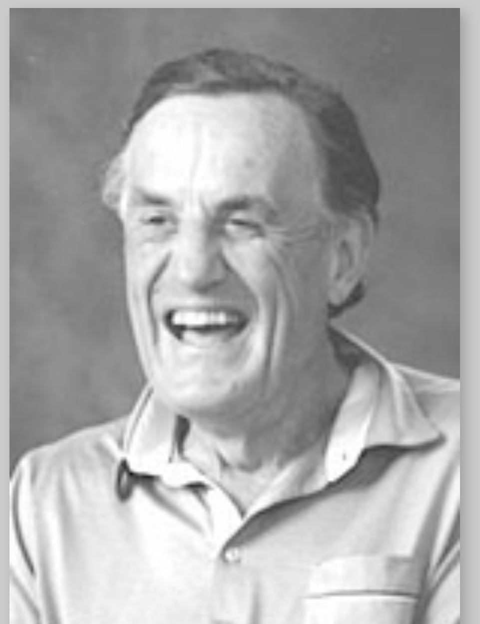


Hanbury-Brown Twiss effect correlates fluctuations at special distances r!

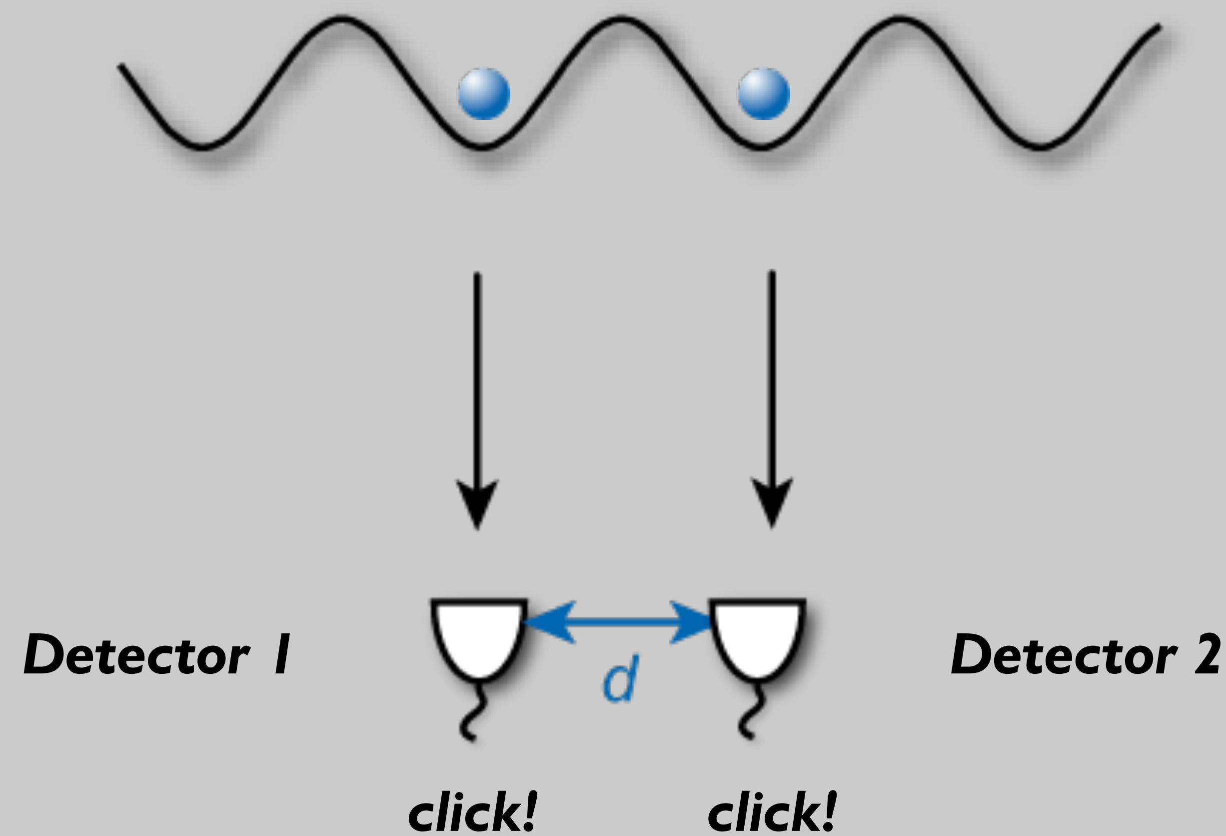
Quantitatively

$g^{(2)}(r)-1>0$	*Noise correlated (Bosons)*
$g^{(2)}(r)-1=0$	*Noise uncorrelated*
$g^{(2)}(r)-1<0$	*Noise anti-correlated (Fermions)*

- Hanbury Brown-Twiss Effect for Atoms (1) -

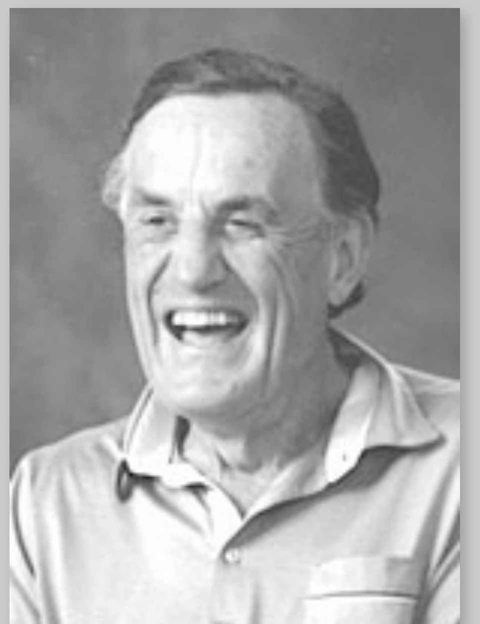


Hanbury Brown
1916-2002

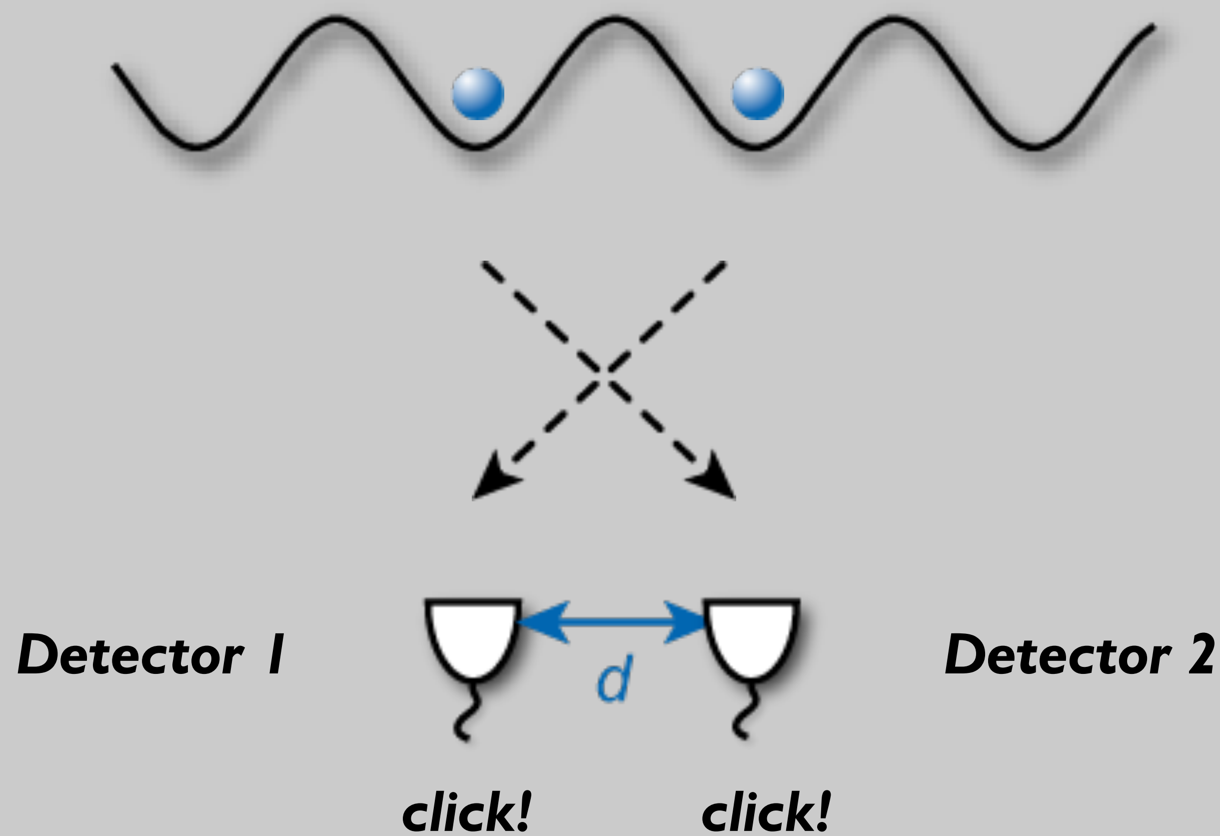


- Hanbury Brown-Twiss Effect for Atoms (2) -

There's another ways....

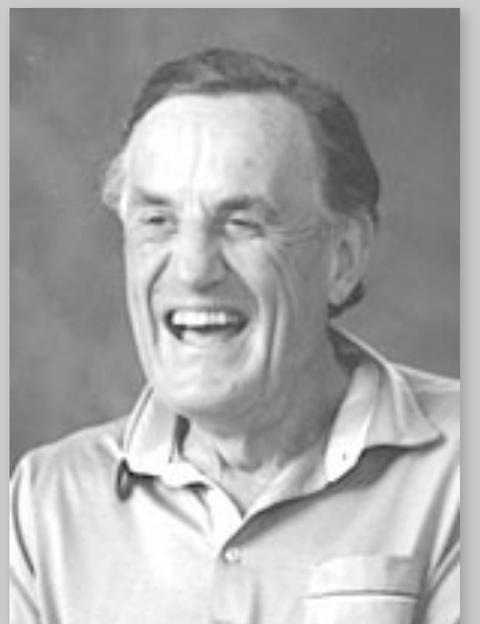


Hanbury Brown
1916-2002

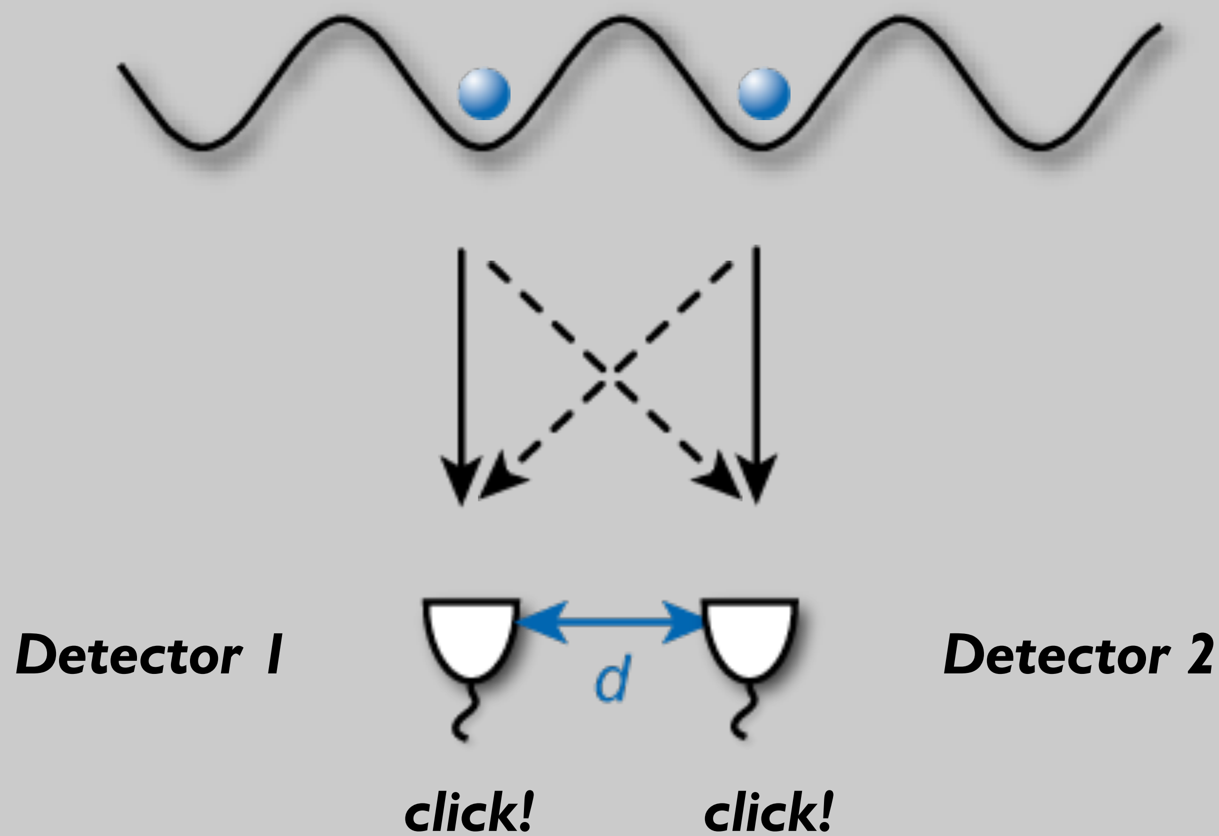


- Hanbury Brown-Twiss Effect for Atoms (3) -

Cannot fundamentally distinguish between both paths...



Hanbury Brown
1916-2002

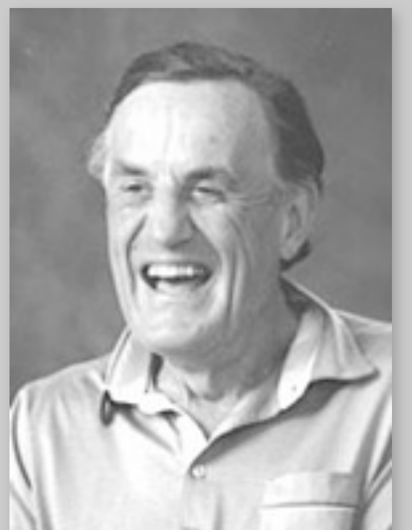


Two Particle Detection probability

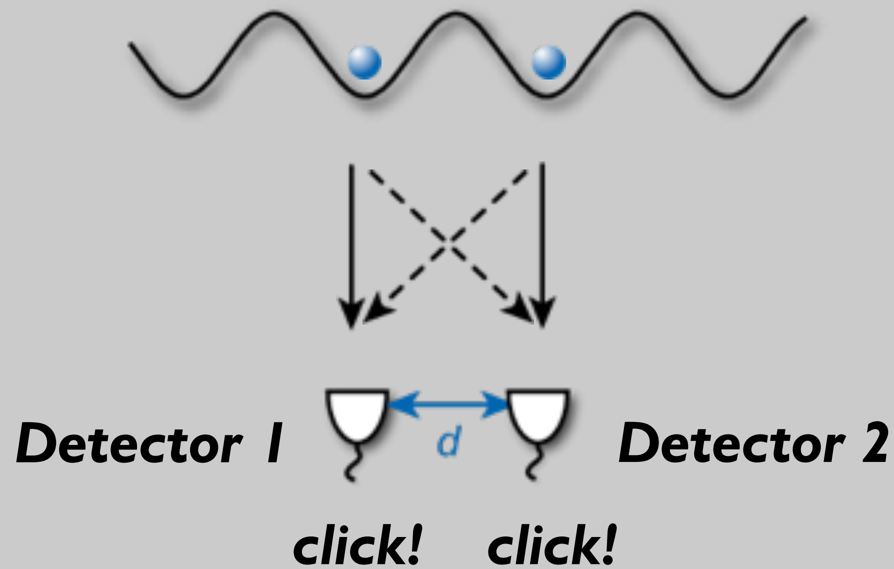
$$\left| \downarrow \quad \downarrow \pm e^{i\phi} \swarrow\!\!\!\!\searrow \right|^2$$

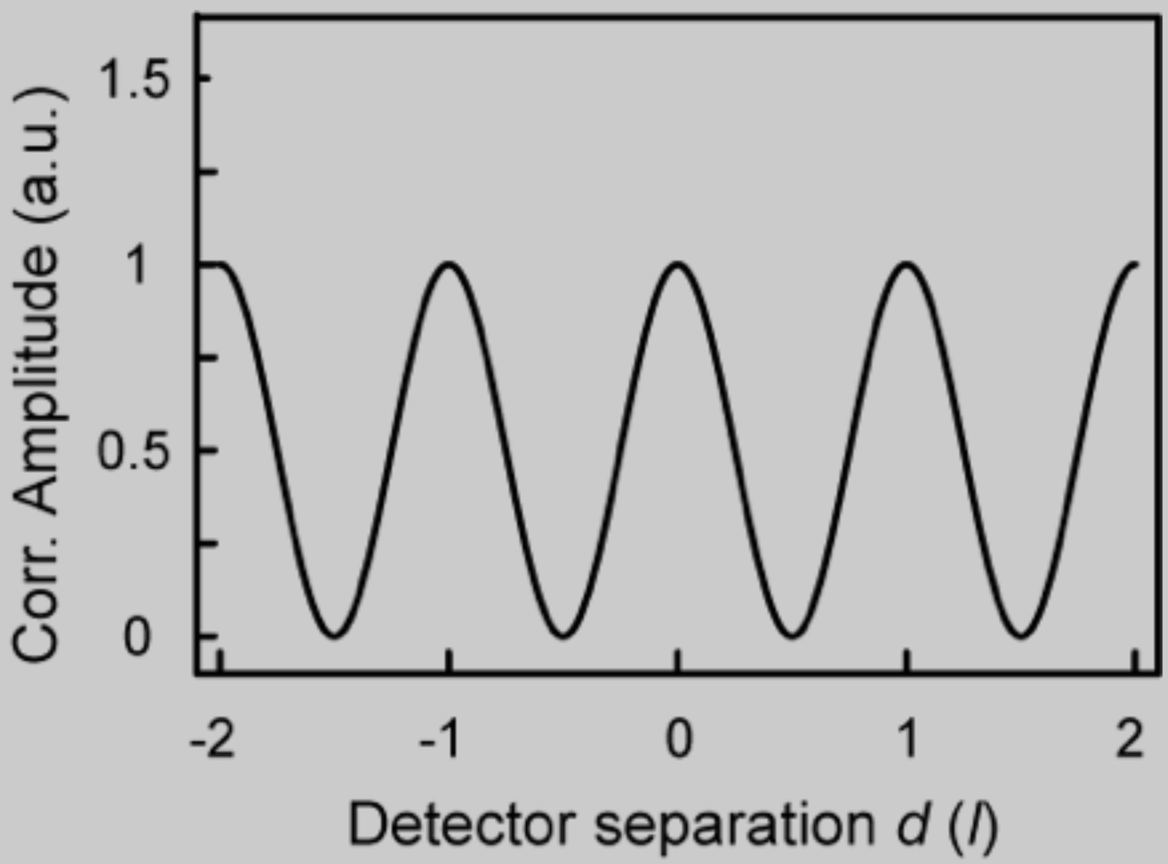
- Hanbury Brown-Twiss Effect for Atoms (4) -

Interference in Two-Particle Detection Probability!



Hanbury Brown
1916-2002

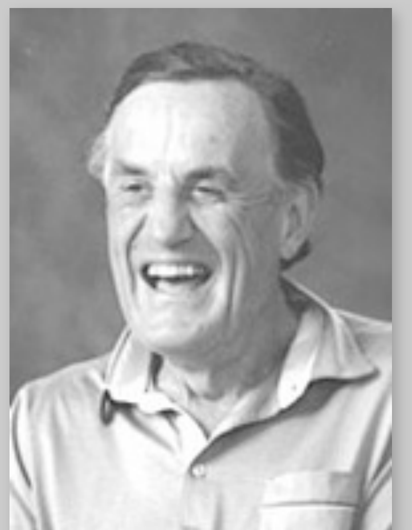




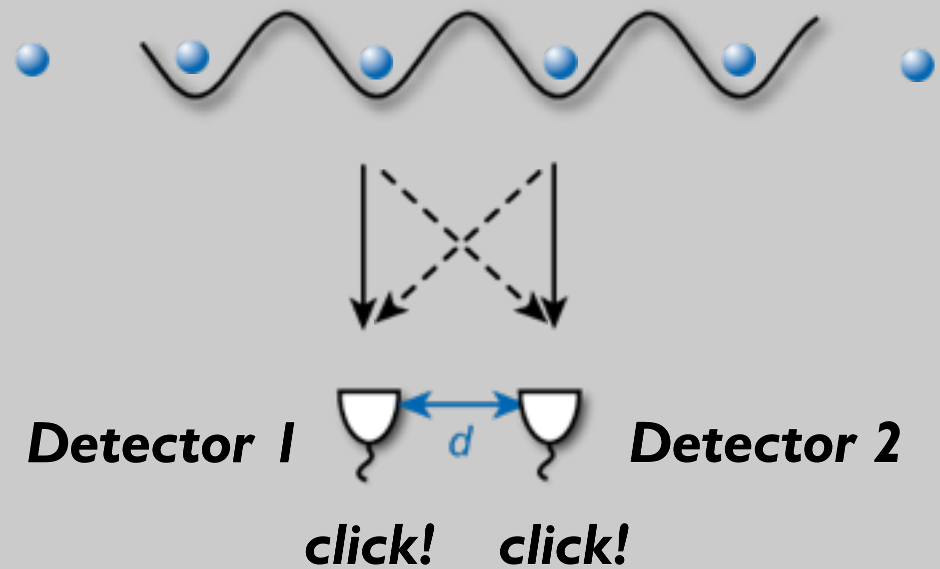
$$l = \frac{h}{m \times a_{lat}} t$$

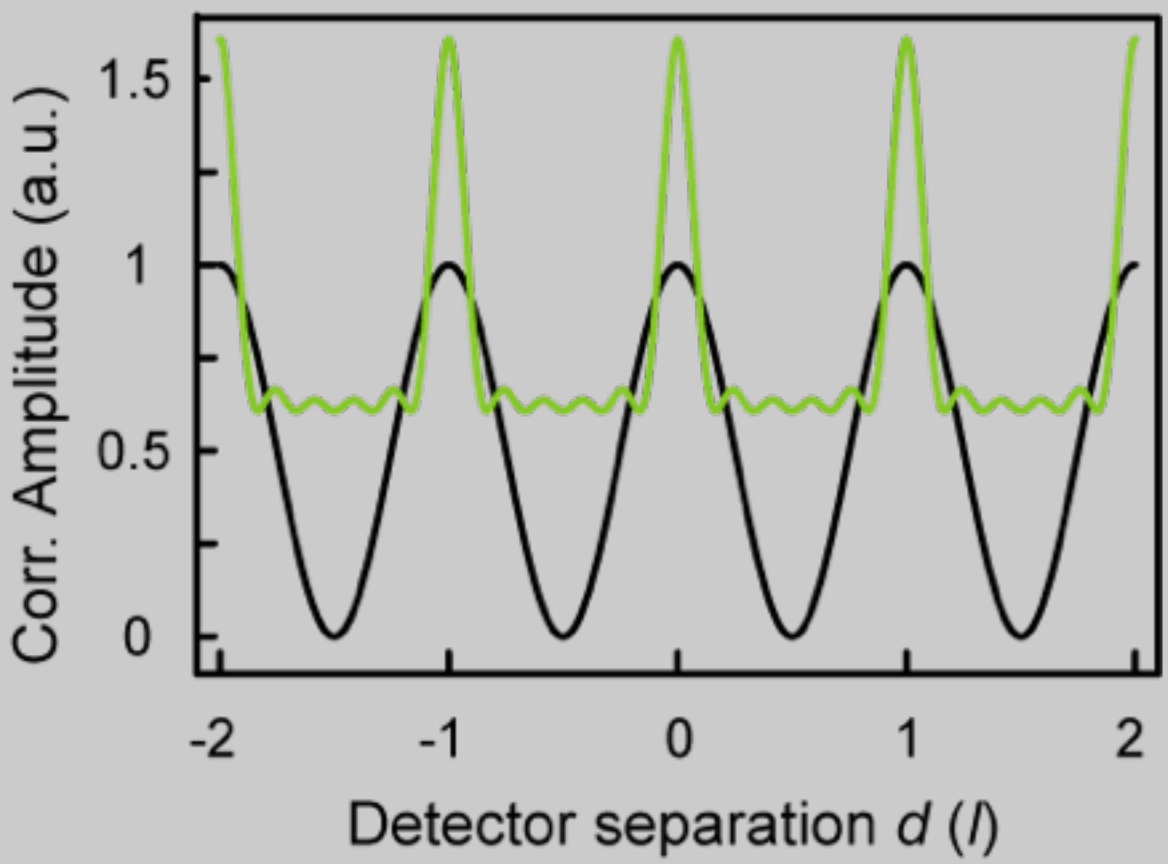
- Multiple Wave Hanbury Brown-Twiss Effect (4) -

Interference in Two-Particle Detection Probability!



Hanbury Brown
1916-2002





$$l = \frac{h}{m a_{lat} t}$$

Deriving the Noise Correlation Signal (1)

In Time of Flight we measure:

$$\begin{aligned}\langle \hat{n}_{3D}(\mathbf{x})\rangle_{\text{tof}} &= \langle \hat{a}^{\dagger}_{tof}(\mathbf{x})\hat{a}_{\text{tof}}(\mathbf{x})\rangle_{\text{tof}} \\ &\approx \langle \hat{a}^{\dagger}(\mathbf{k})\hat{a}(\mathbf{k})\rangle_{\text{trap}} = \langle \hat{n}_{3D}(\mathbf{k})\rangle_{\text{trap}}\end{aligned}$$

where $\boxed{\mathbf{k} = M\mathbf{x}/\hbar t}$

In Noise Correlations we measure:

$$\boxed{\begin{aligned}&\langle \hat{n}_{3D}(\mathbf{x})\hat{n}_{3D}(\mathbf{x}')\rangle_{\text{tof}} \approx \langle \hat{a}^{\dagger}(\mathbf{k})\hat{a}(\mathbf{k})\hat{a}^{\dagger}(\mathbf{k}')\hat{a}(\mathbf{k}')\rangle_{\text{trap}} = \\ &\langle \hat{a}^{\dagger}(\mathbf{k})\hat{a}^{\dagger}(\mathbf{k}')\hat{a}(\mathbf{k}')\hat{a}(\mathbf{k})\rangle_{\text{trap}} + \delta_{\mathbf{k}\mathbf{k}'}\langle \hat{a}^{\dagger}(\mathbf{k})\hat{a}(\mathbf{k})\rangle_{\text{trap}} \quad .\end{aligned}}$$

Deriving the Noise Correlation Signal (2)

$$\hat{a}(\mathbf{k}) = \int e^{-i\mathbf{k}\mathbf{r}}\hat{\psi}(\mathbf{r})d^3r$$ with $$\hat{\psi}(\mathbf{r}) = \sum_{\mathbf{R}} \hat{a}_{\mathbf{R}} w(\mathbf{r}-\mathbf{R})$$

$$\Rightarrow \quad \hat{a}(\mathbf{k}) = \tilde{w}(\mathbf{k}) \sum_{\mathbf{R}} e^{-i\mathbf{k}\mathbf{R}} \hat{a}_{\mathbf{R}}$$

Plug this into four operator correlator

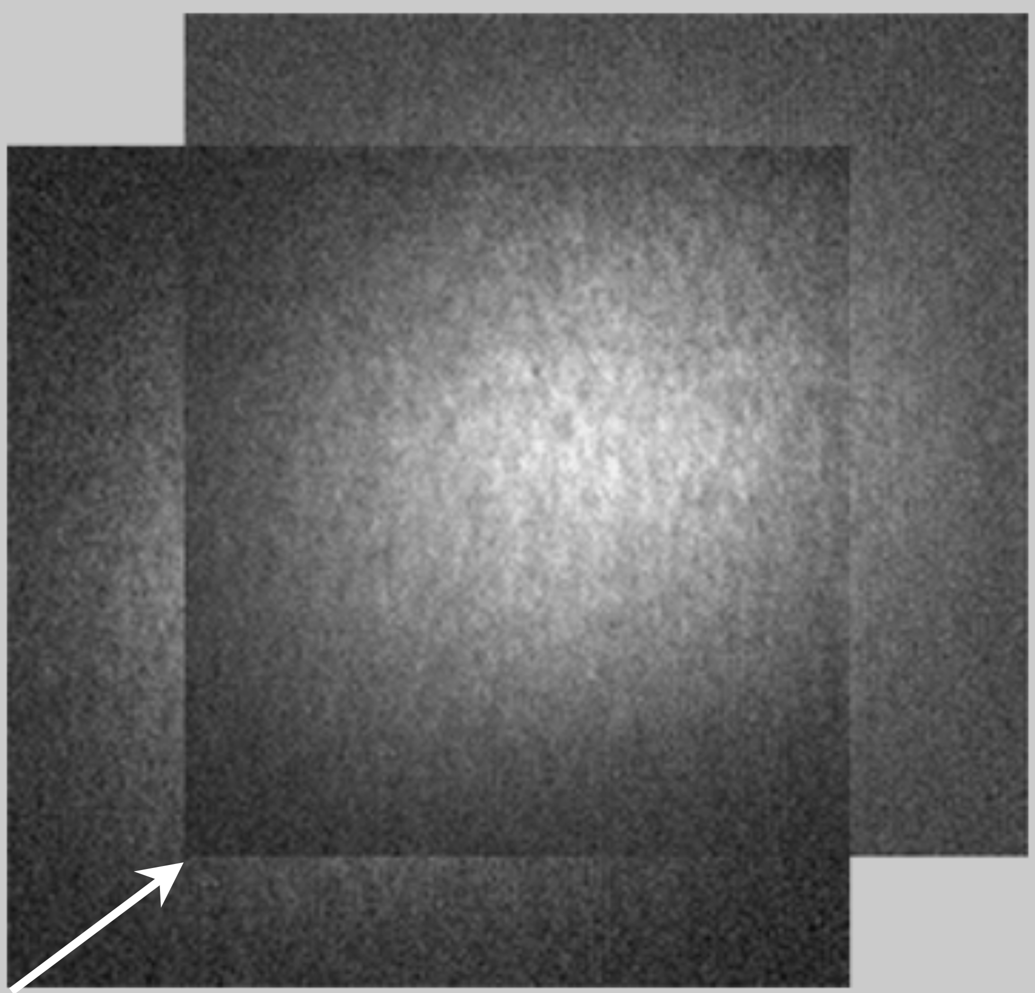
For Mott state or Fermi gas, one has $\langle \hat{a}^{\dagger}_{\mathbf{R}} \hat{a}_{\mathbf{R}'} \rangle = n_{\mathbf{R}} \delta_{\mathbf{R},\mathbf{R}'}$

which yields:

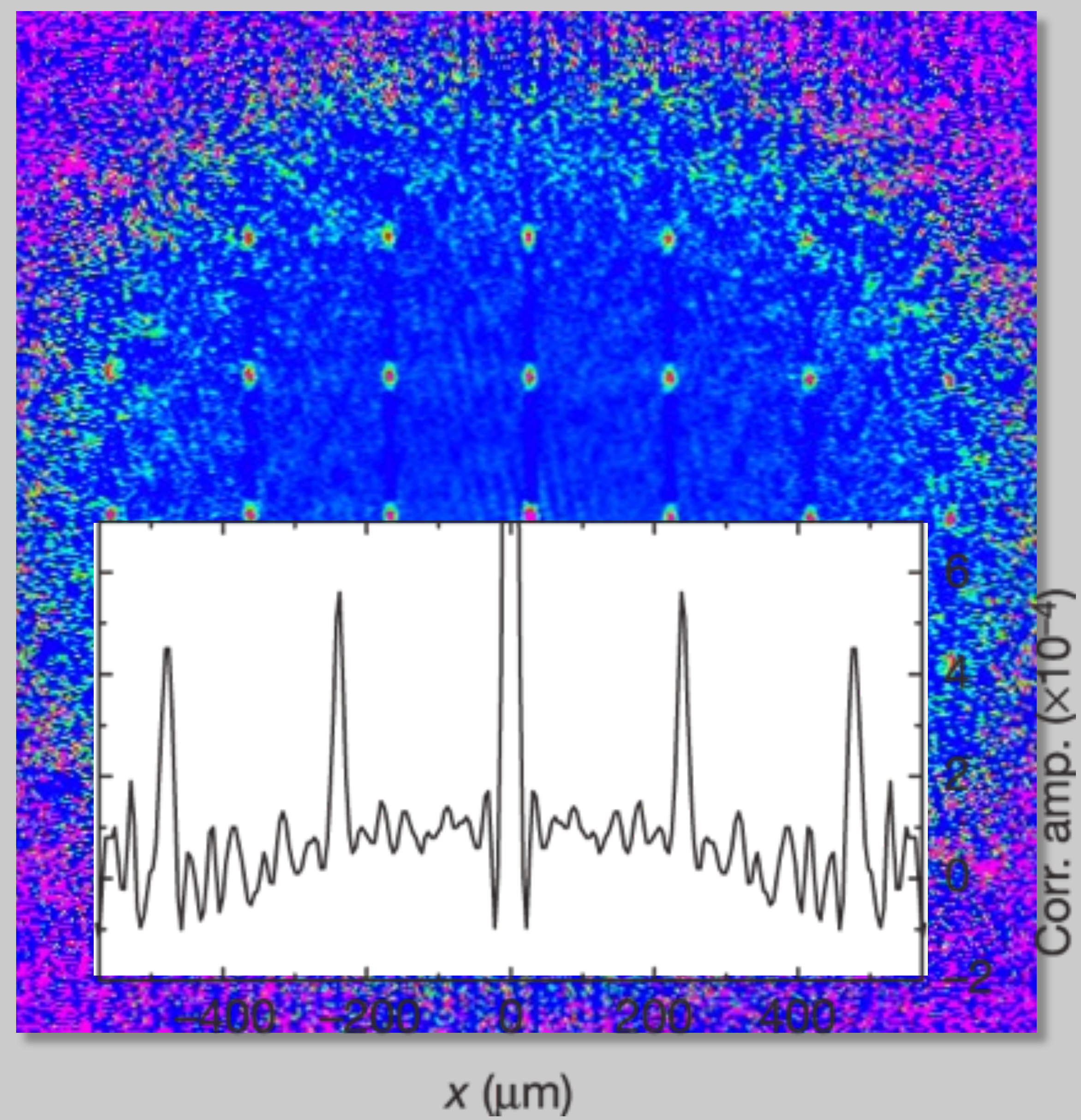
$$\langle \hat{n}_{3D}(\mathbf{x}) \hat{n}_{3D}(\mathbf{x}') \rangle = |\tilde{w}(M\mathbf{x}/\hbar t)|^2 |\tilde{w}(M\mathbf{x}'/\hbar t)|^2 N^2 \times \left[1 \pm \frac{1}{N^2} \left| \sum_{\mathbf{R}} e^{i(\mathbf{x}-\mathbf{x}')\cdot\mathbf{R}(M/\hbar t)} n_{\mathbf{R}} \right|^2 \right]$$

Information in the Noise – Correlations become visible!

$$g^{(2)}_{\mathrm{exp}}(\mathbf{b}) = \frac{\int \langle n(\mathbf{x}+\mathbf{b}/2)\cdot n(\mathbf{x}-\mathbf{b}/2)\rangle\, d^2\mathbf{x}}{\int \langle n(\mathbf{x}+\mathbf{b}/2)\rangle\langle n(\mathbf{x}-\mathbf{b}/2)\rangle\, d^2\mathbf{x}}$$

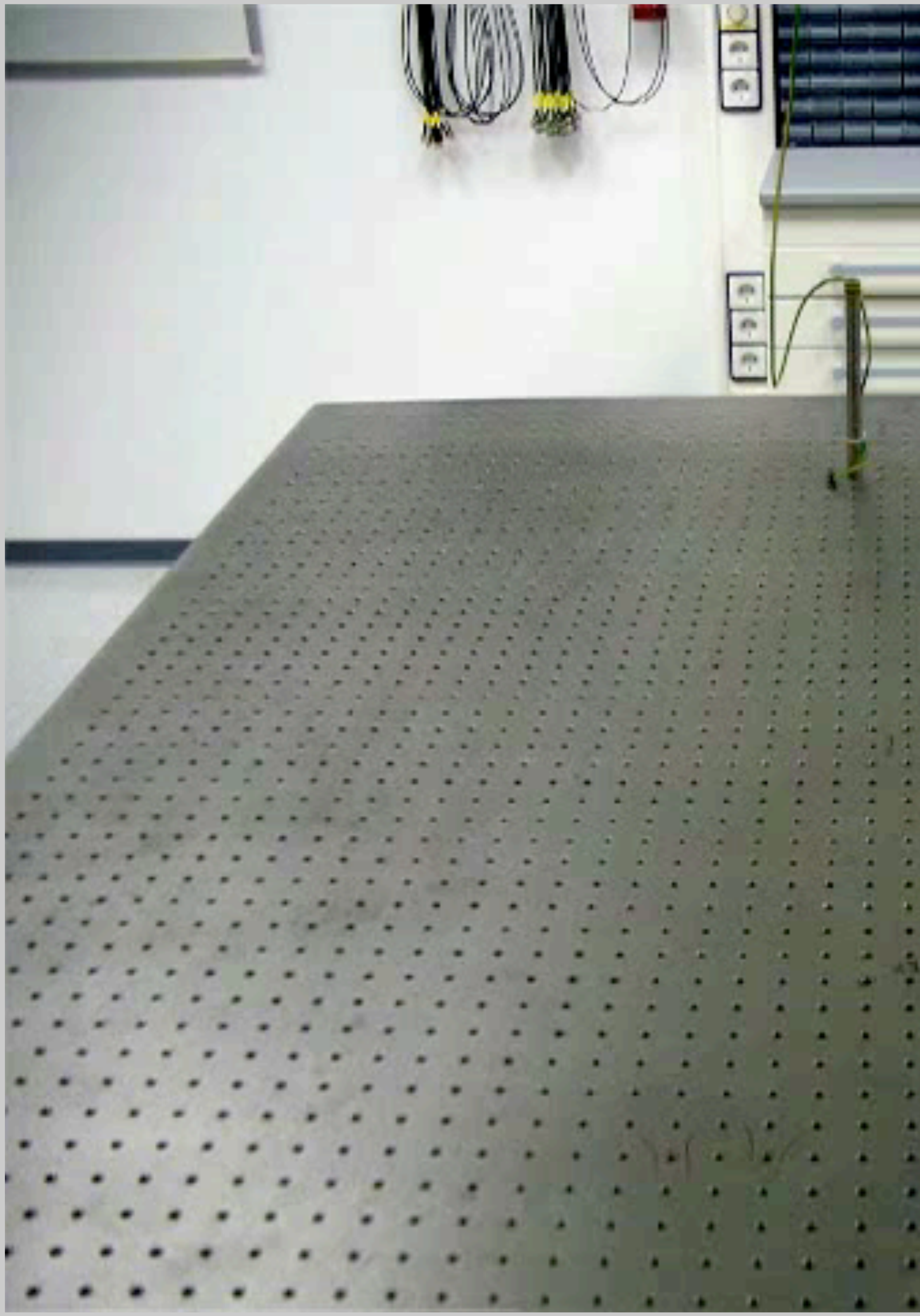


Fölling et al. Nature, 434, p. 481(2005)

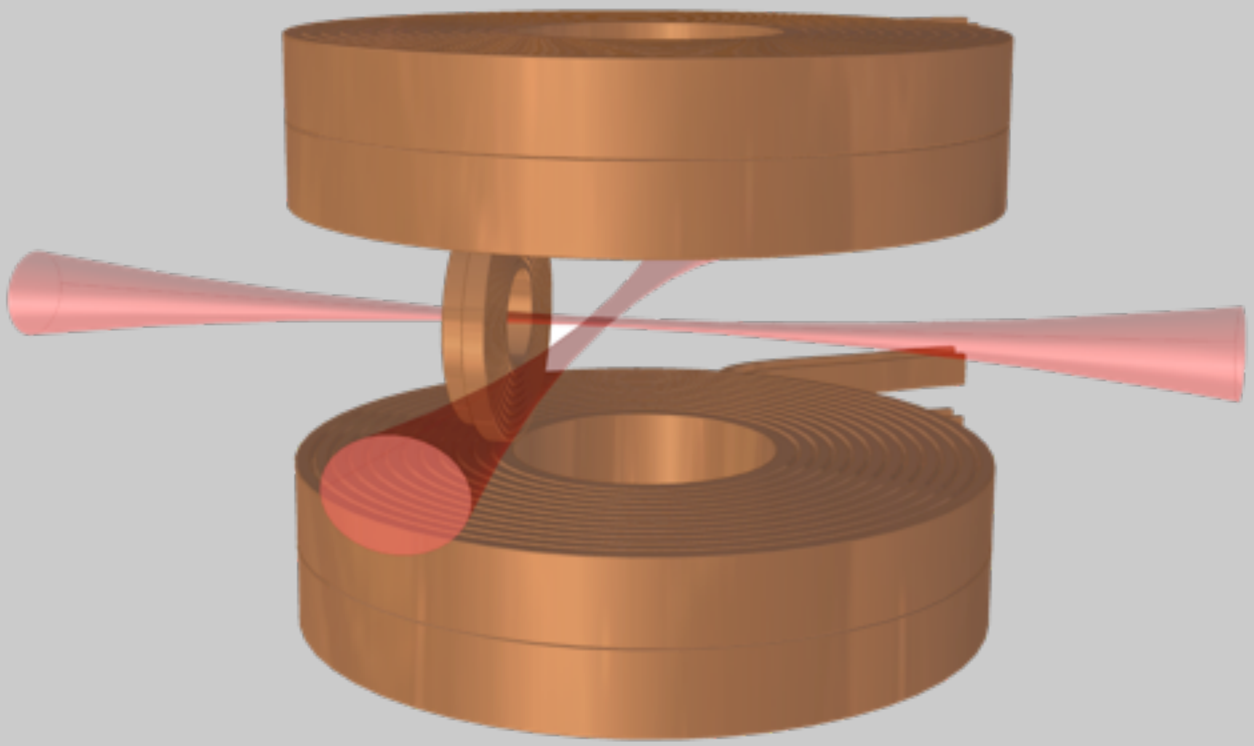


Correlation function!

Let's change the sign…



Sympathetic Cooling of ^{40}K-^{87}Rb in Crossed Dipole Trap:



After final cooling in optical dipole trap

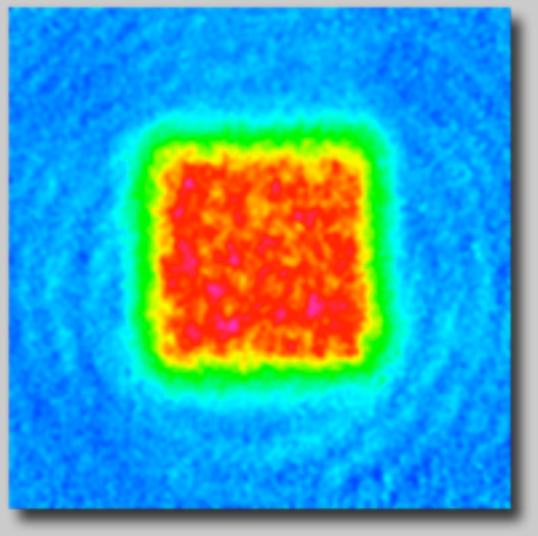
2×10^5 ^{87}Rb (almost pure condensate)

2.5×10^5 ^{40}K

After removal of ^{87}Rb

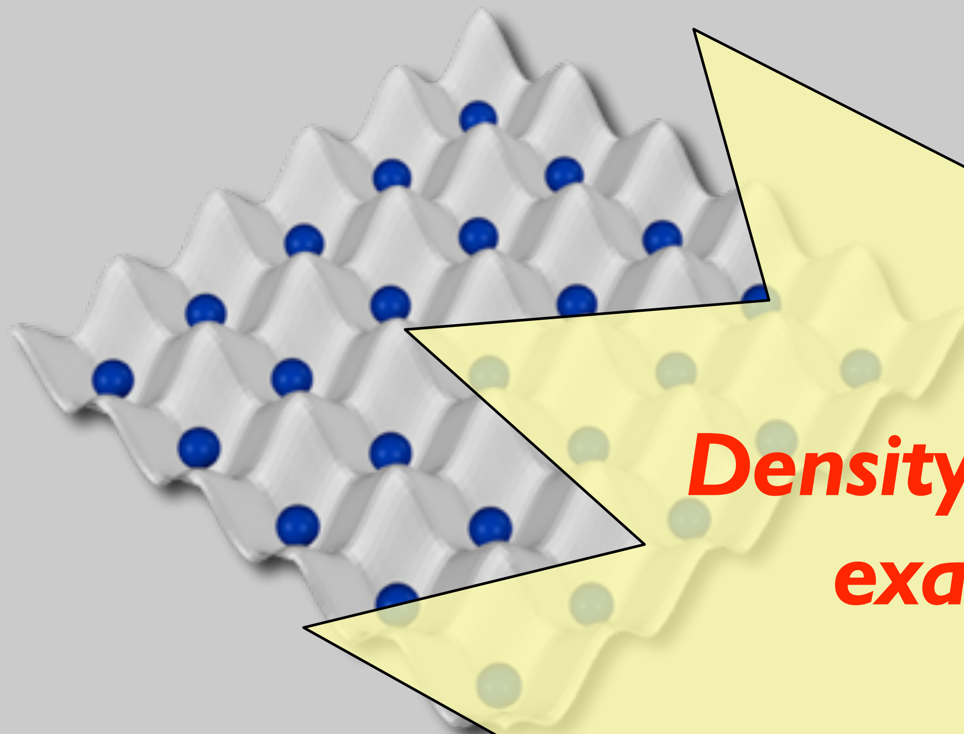
2×10^5 ^{40}K @ $T/T_F=0.2$

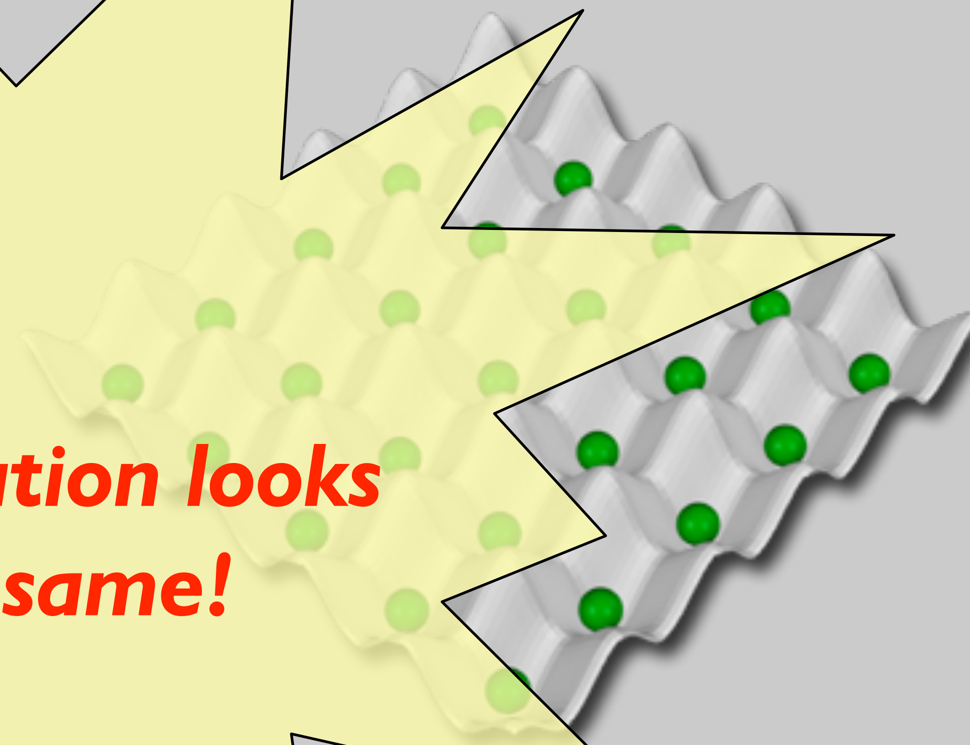
Then load into 3D optical lattice and create a fermionic band insulator!



Adiabatic mapping:
theory: A. Kastberg et al. PRL (1995)
exp: M. Greiner et al., PRL (2001), M. Köhl et al. PRL (2005)

Mott insulator – Fermionic Band Insulator





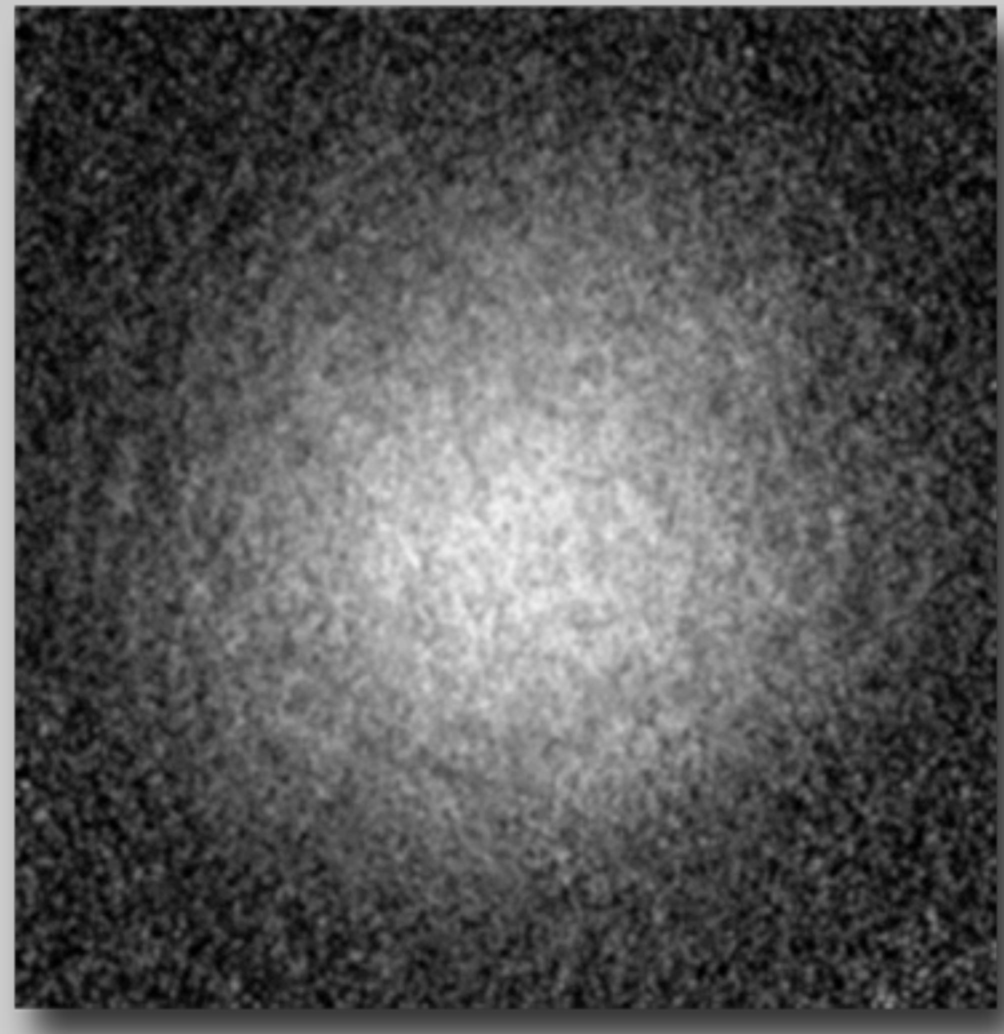
Density distribution looks exactly the same!

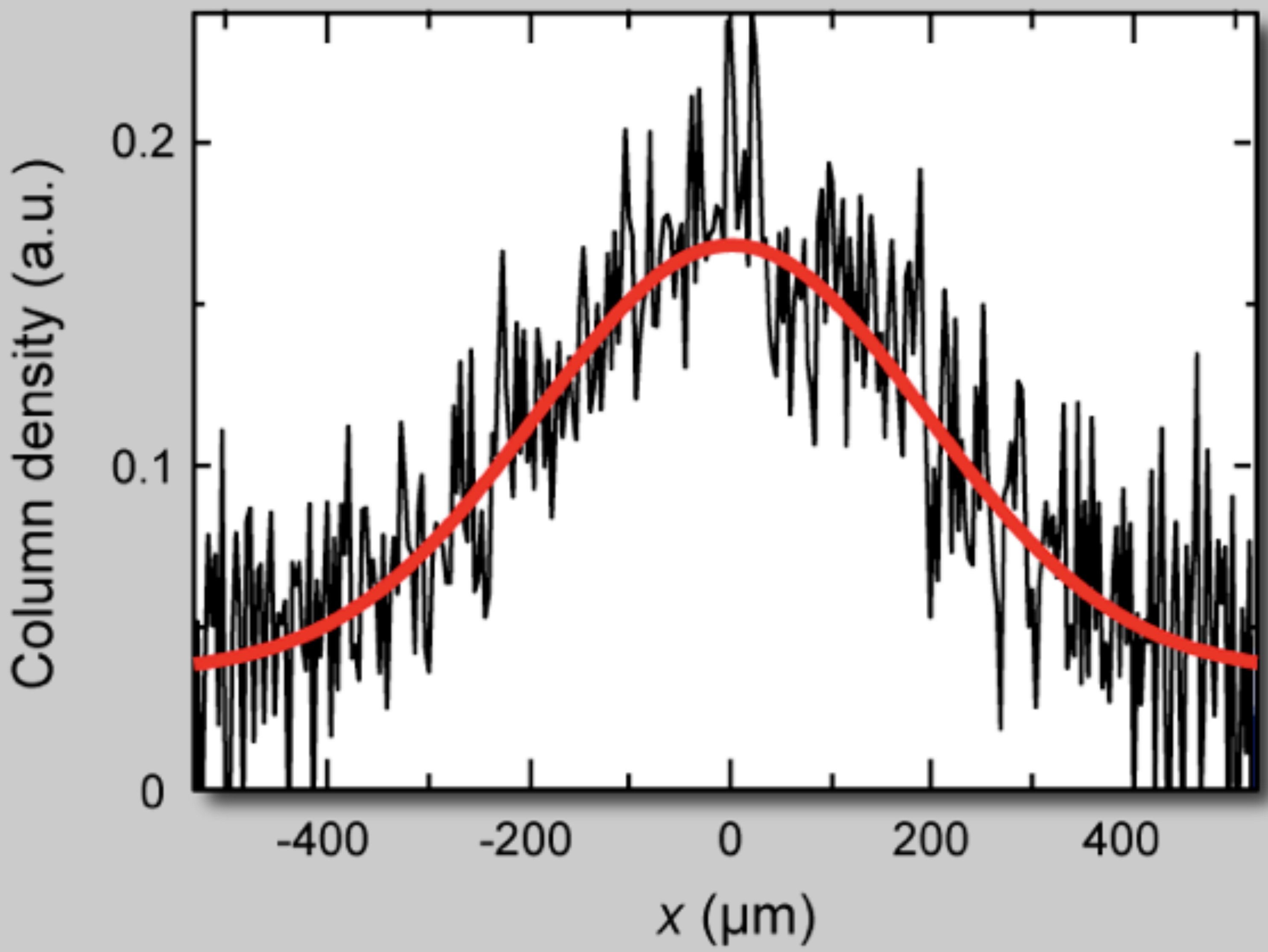
Mott insulator

Fermionic band insulator

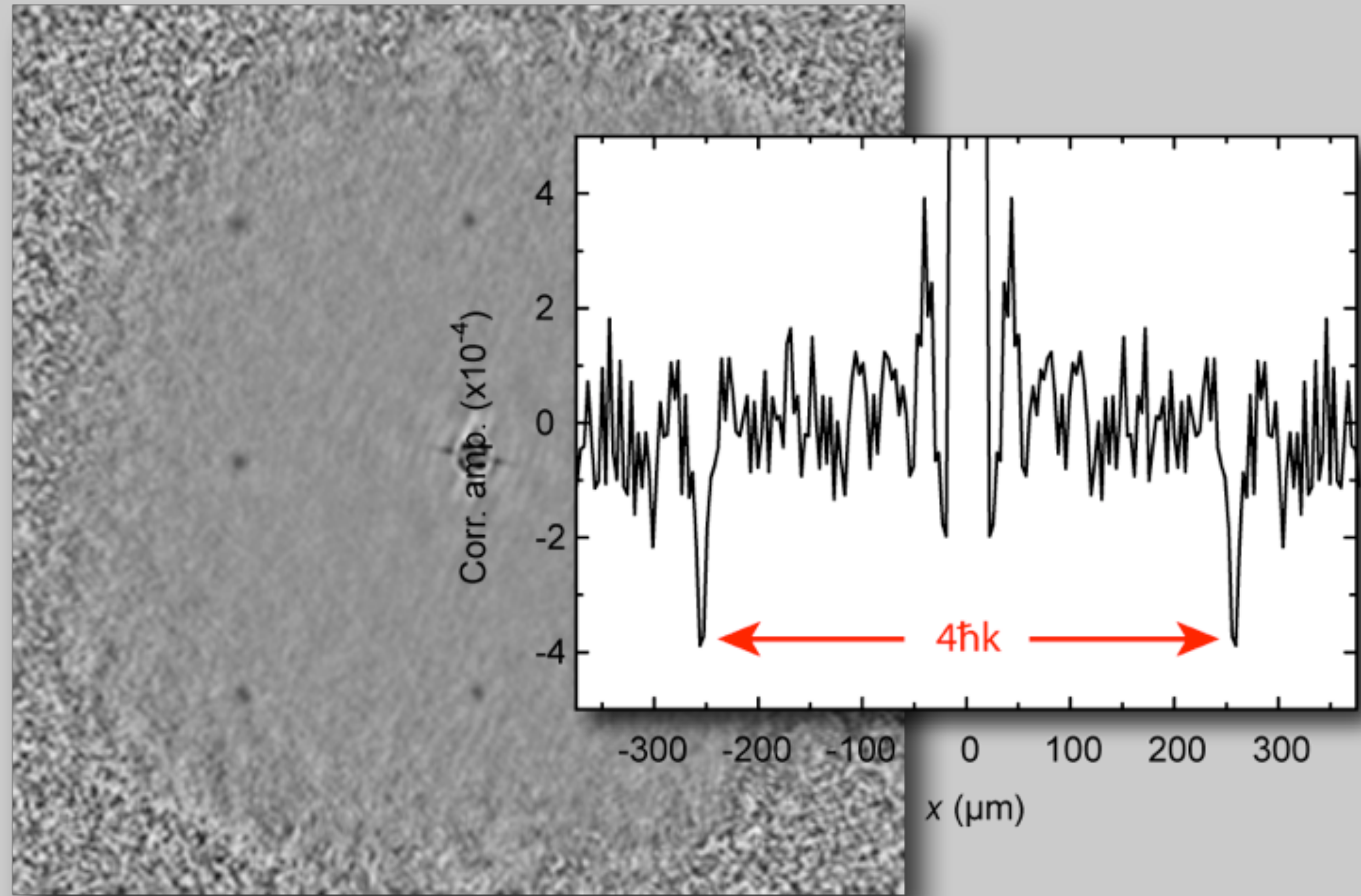
Dominating repulsive interactions mimic Pauli principle!

Releasing the Fermi Gas





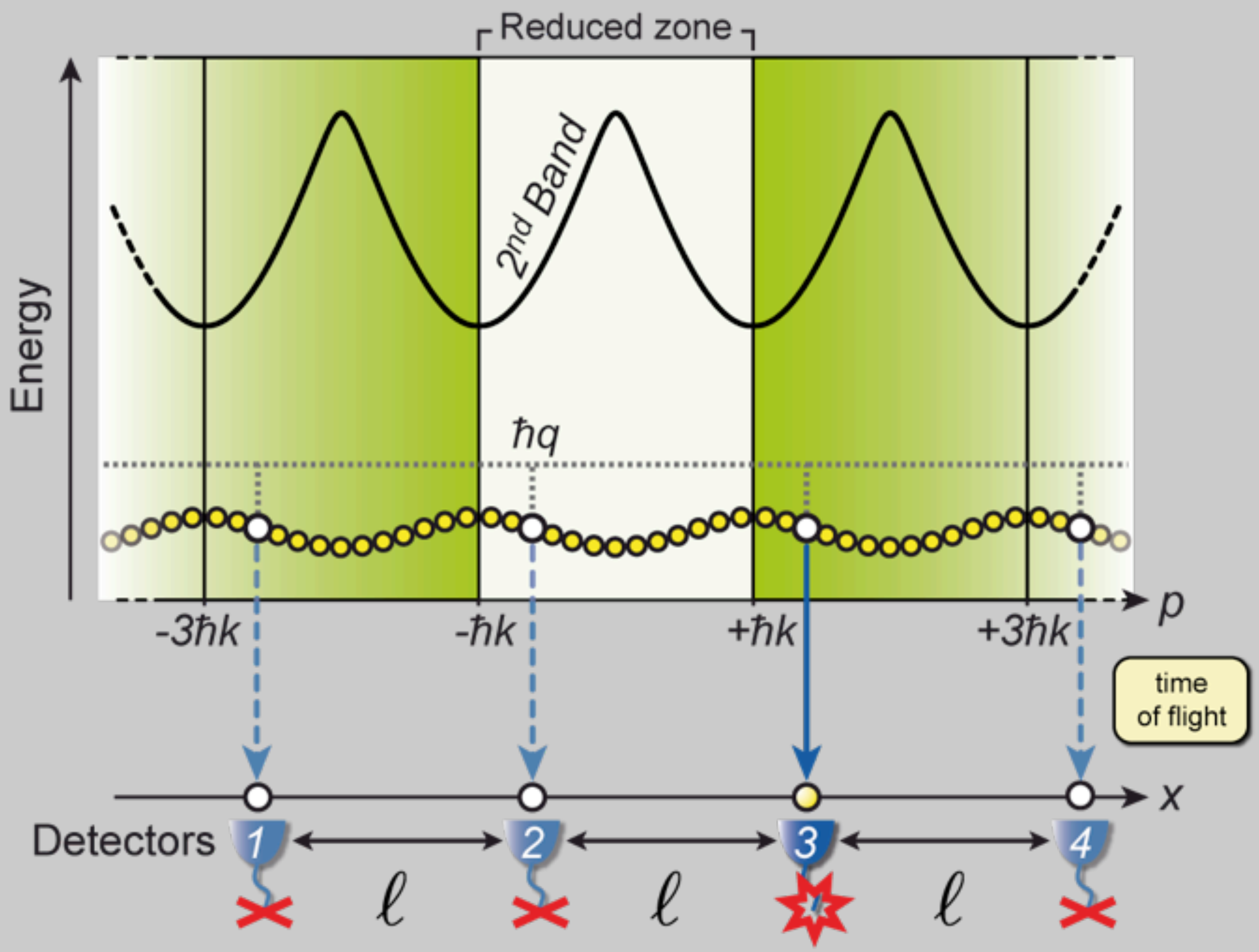
Noise Correlations of a Degenerate Fermi Gas



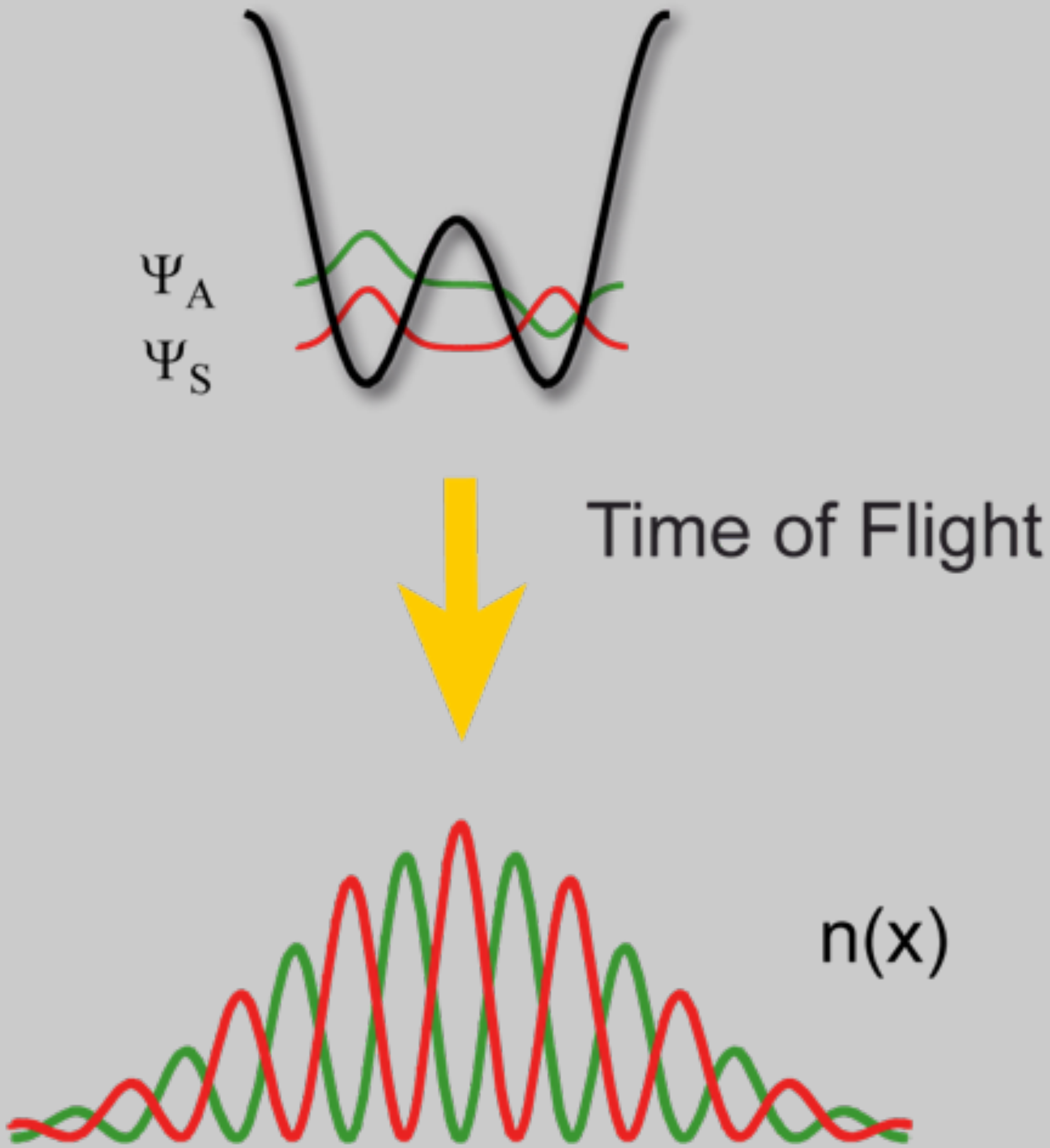
Rom et al.
Nature **444**, 733 (2006)

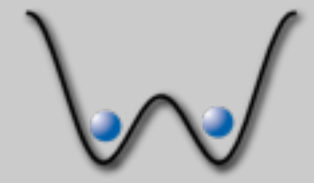
First observation of fermionic antibunching for neutral atoms (maybe neutral particles)! (see also Jeltes et al., Nature **445**, 402 (2007))

An Alternative Description



Why Bosons and Fermions are Different in their Correlations





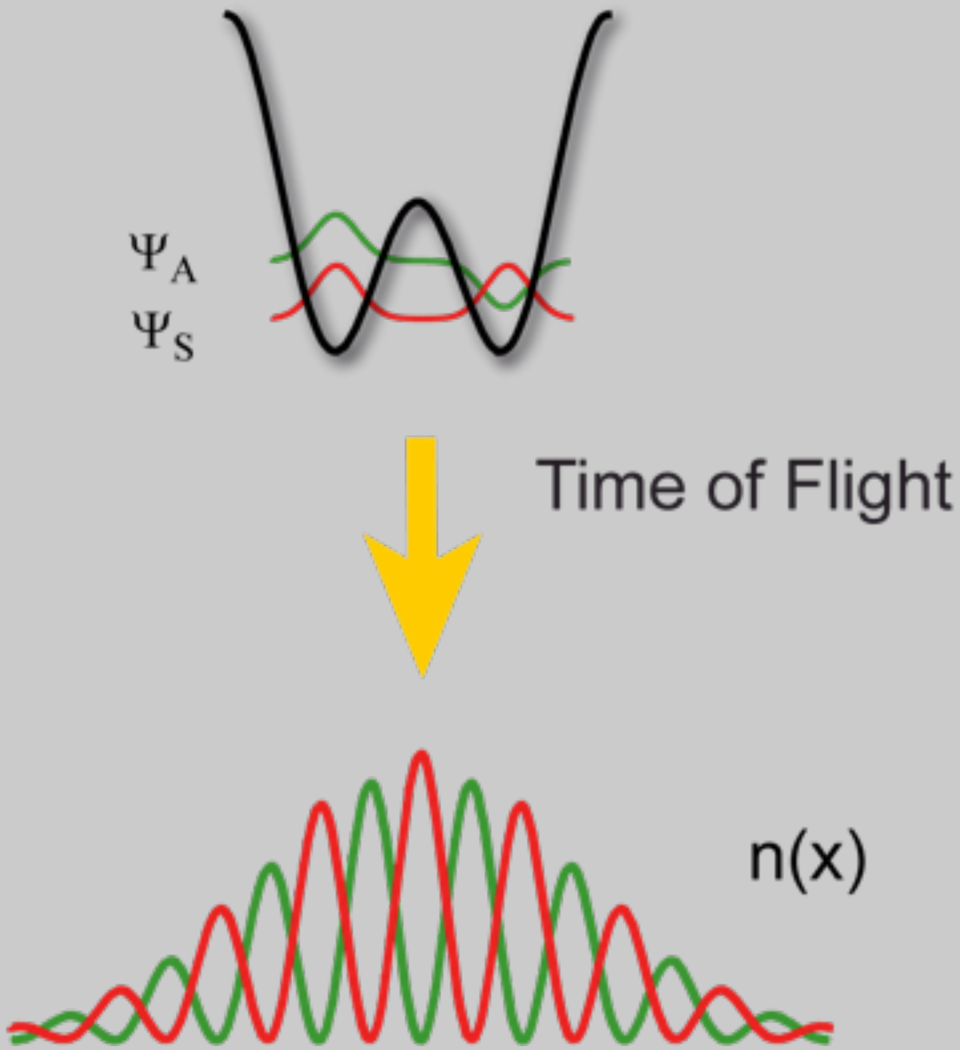
Bosons

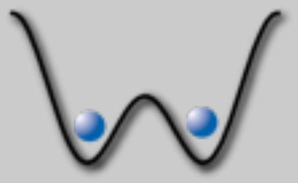
$$\Psi_L \otimes \Psi_R + \Psi_R \otimes \Psi_L$$

$$\Updownarrow$$

$$\Psi_S \otimes \Psi_S + \Psi_A \otimes \Psi_A$$

Why Bosons and Fermions are Different in their Correlations





Bosons

$$\Psi_L \otimes \Psi_R + \Psi_R \otimes \Psi_L$$

$$\Updownarrow$$

$$\Psi_S \otimes \Psi_S + \Psi_A \otimes \Psi_A$$

Fermions

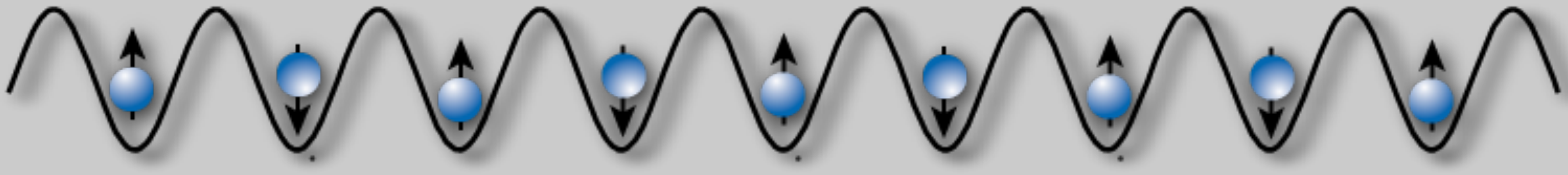
$$\Psi_L \otimes \Psi_R - \Psi_R \otimes \Psi_L$$

$$\Updownarrow$$

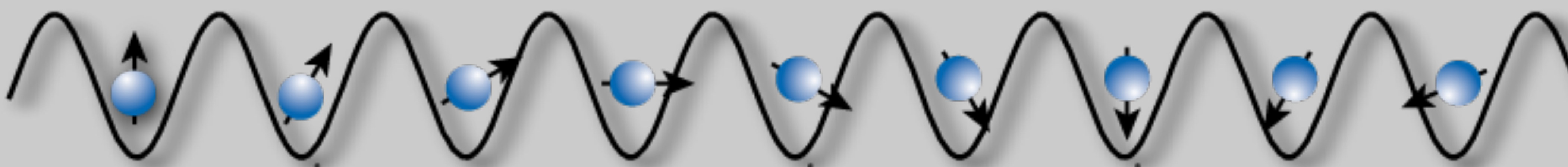
$$\Psi_S \otimes \Psi_A - \Psi_A \otimes \Psi_S$$

Now detection of many strongly correlated quantum states becomes possible!

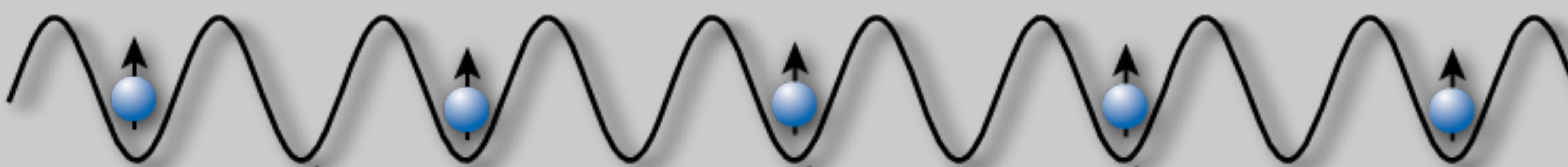
Antiferromagnet



Spin wave

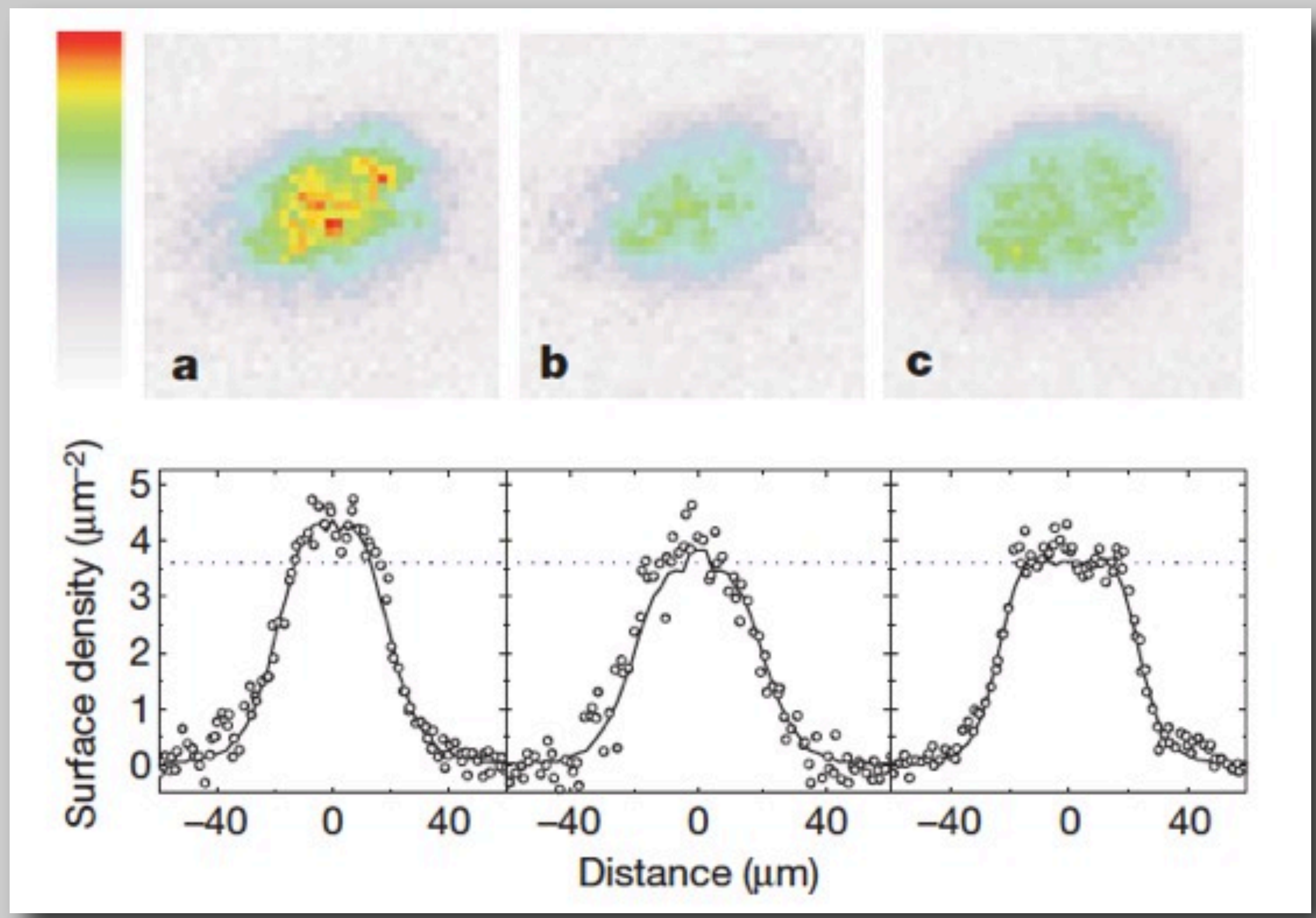


Charge density wave



In Situ Density Measurements

Absorption Imaging

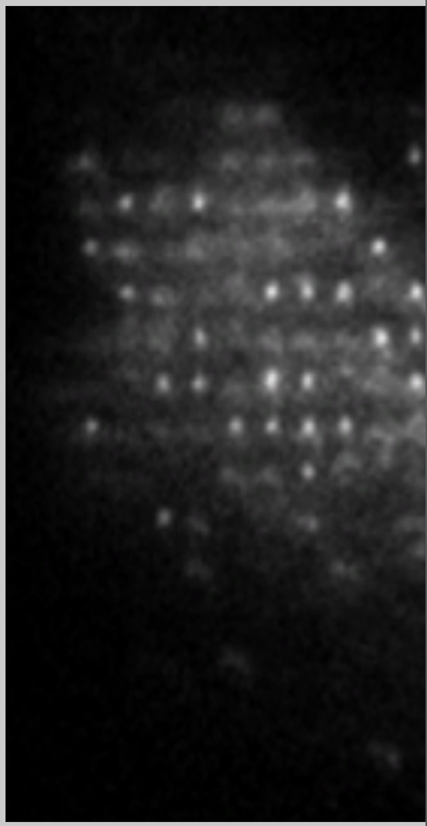


Absorption per atom maximally approx 5-10% (typically smaller), mode-matching!

N. Gemelke et al., Nature **460**, 995 (2009)

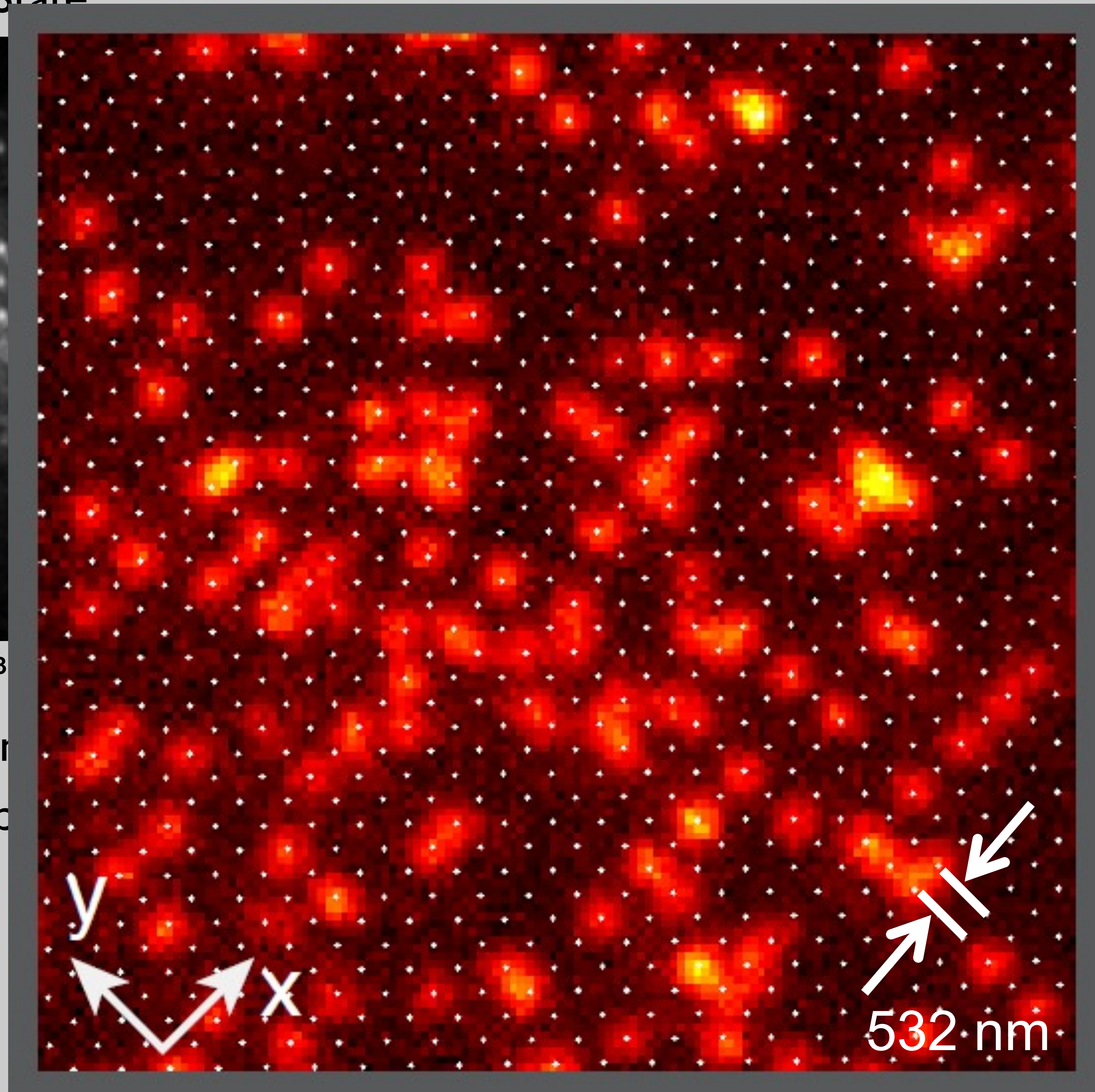
State of the Art

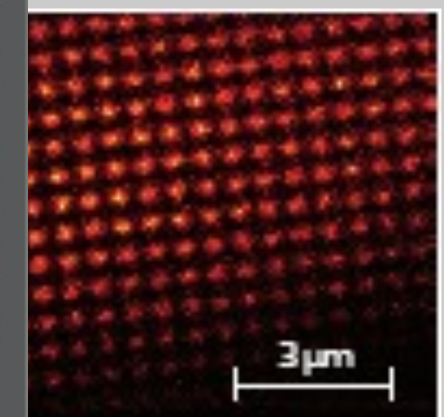
D. Weiss, Penn State



Nelson *et al.*, Nature Phys. **3**

- fluorescence i
- 5 μm lattice sp





9)

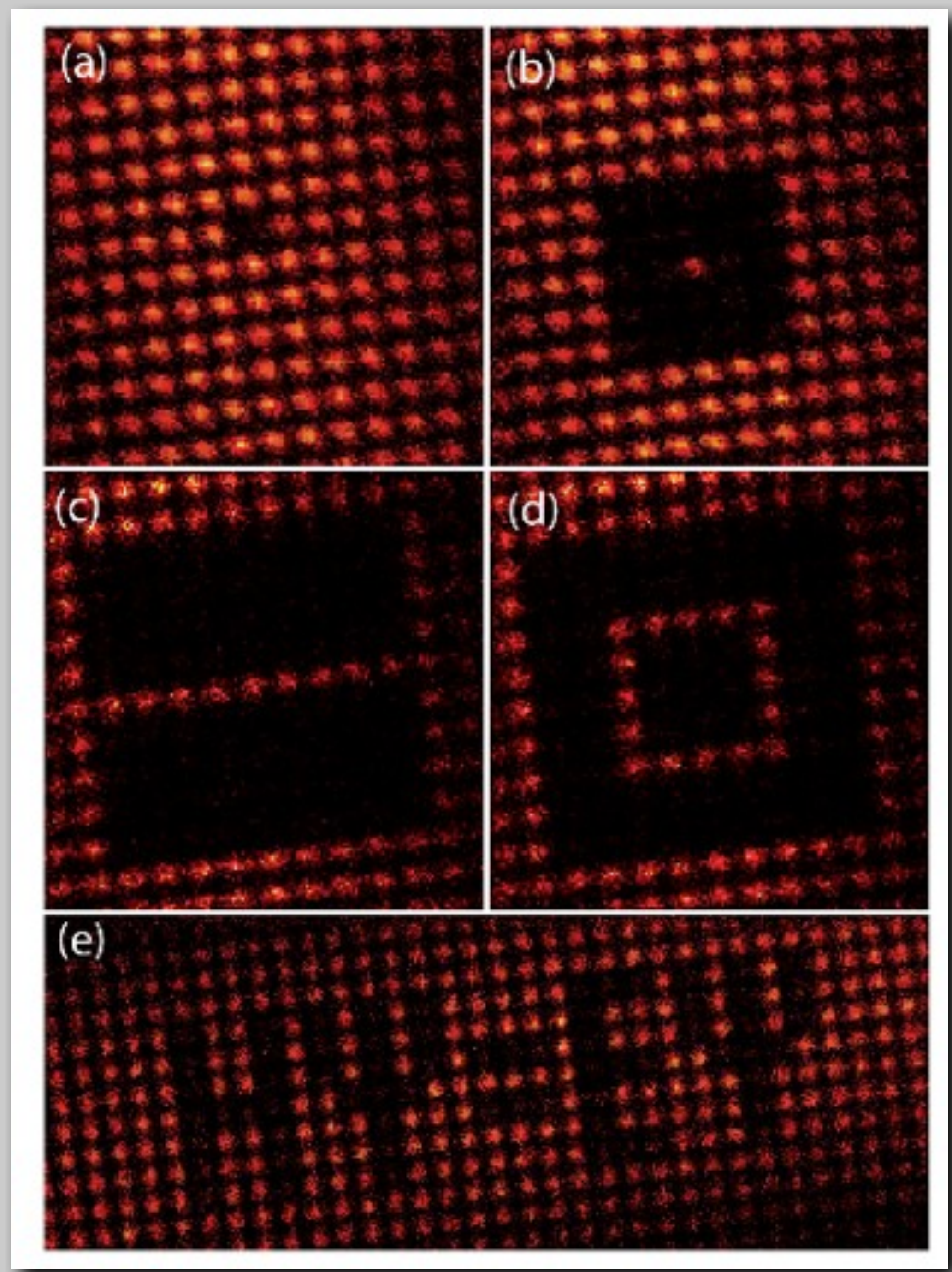
Harvard

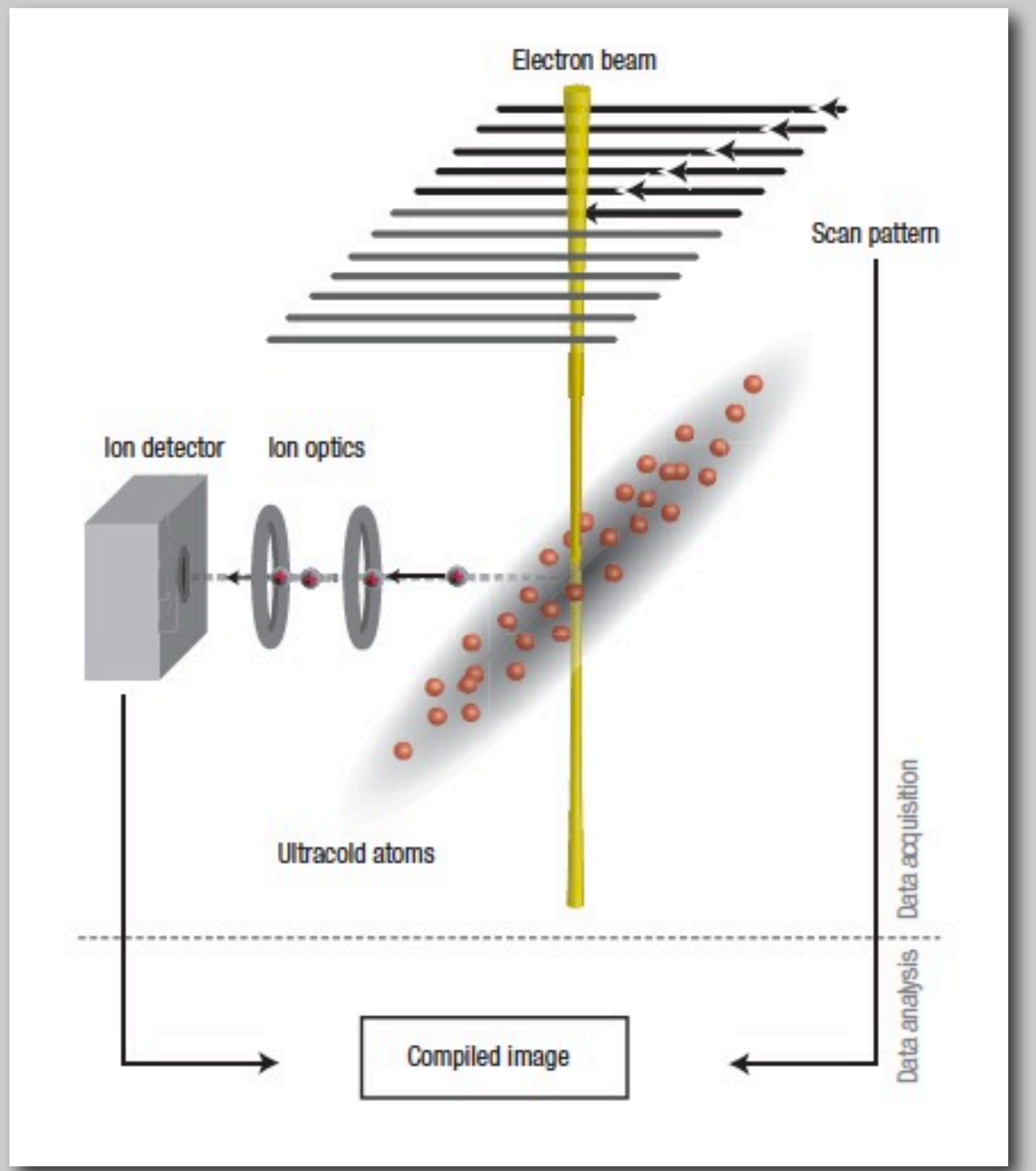
in surface trap

ttice spacing

462, 74-77 (2009)

Detecting Atoms with an Electron Beam





P. Würtz et al., PRL (2009)

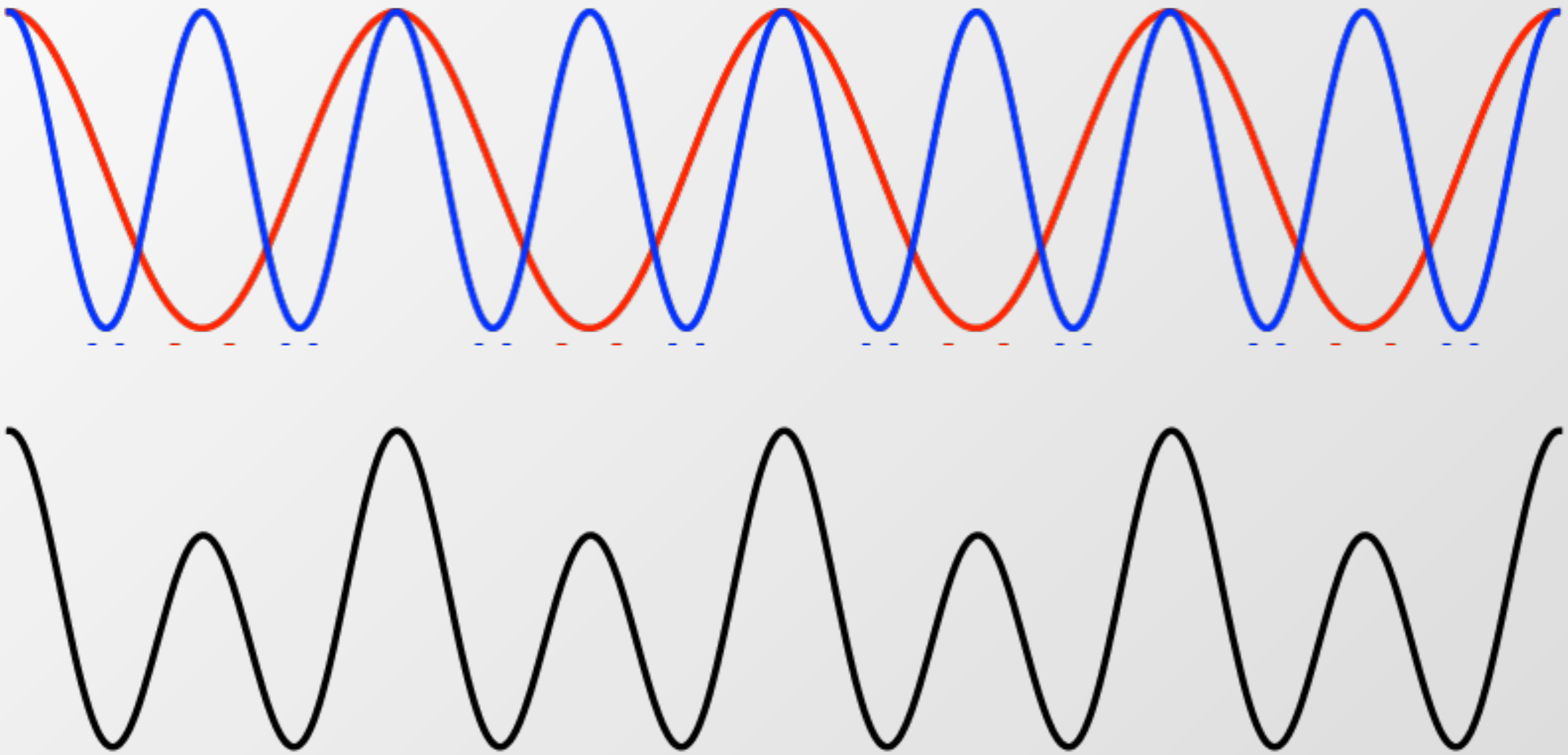
Optical Superlattices

See also Related Experiments at NIST (T. Porto & W. D. Phillips)

Optical Superlattices

Superimpose two standing waves **with controllable phase & amplitude.**

1530 nm + 765 nm



Array of double wells

Controllable Parameters

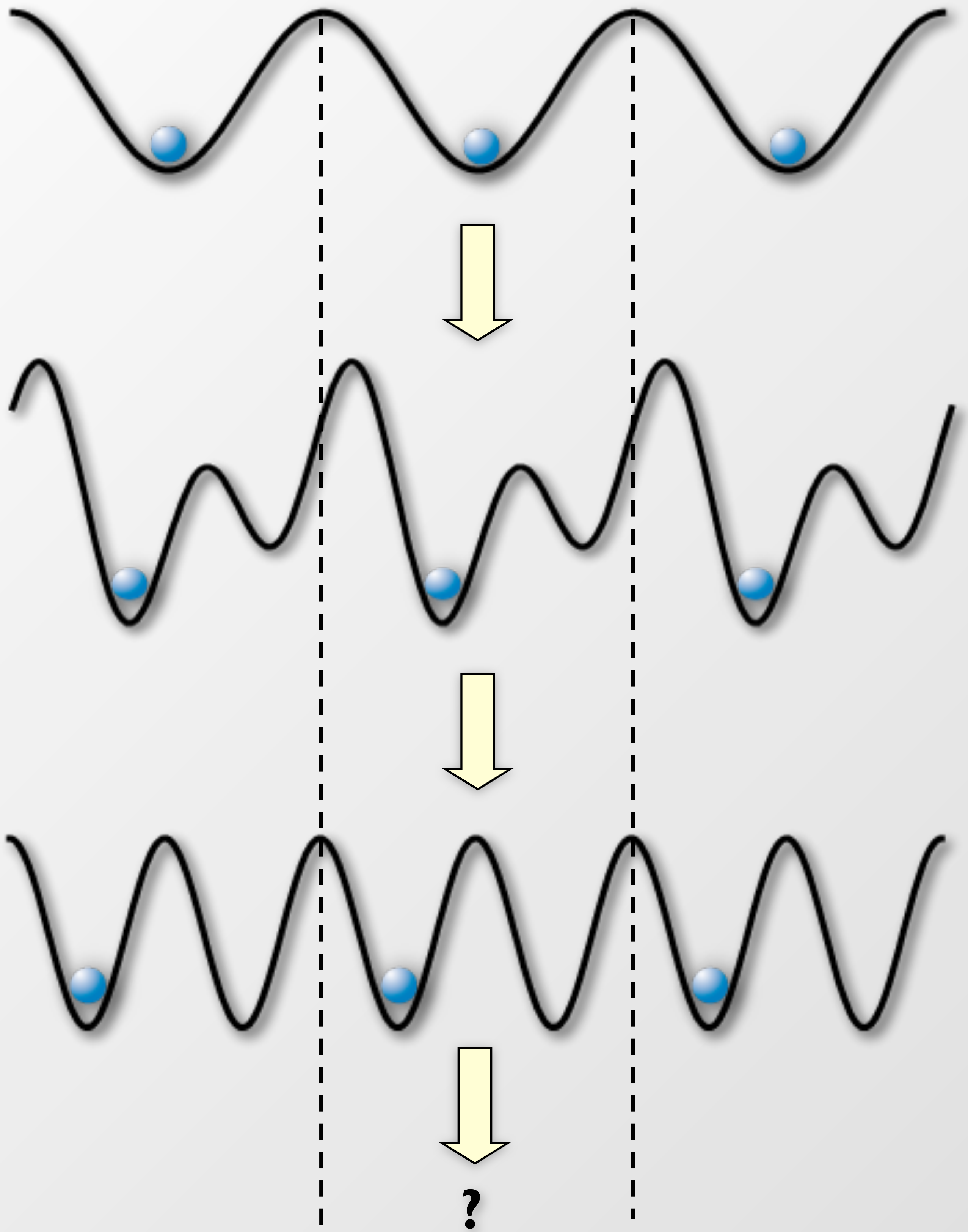
- **Original**

- **Intra & Interwell Barrier Depth**

- **Potential Bias**

All parameters can be changed dynamically & in-situ!

Patterned loading of the short lattice



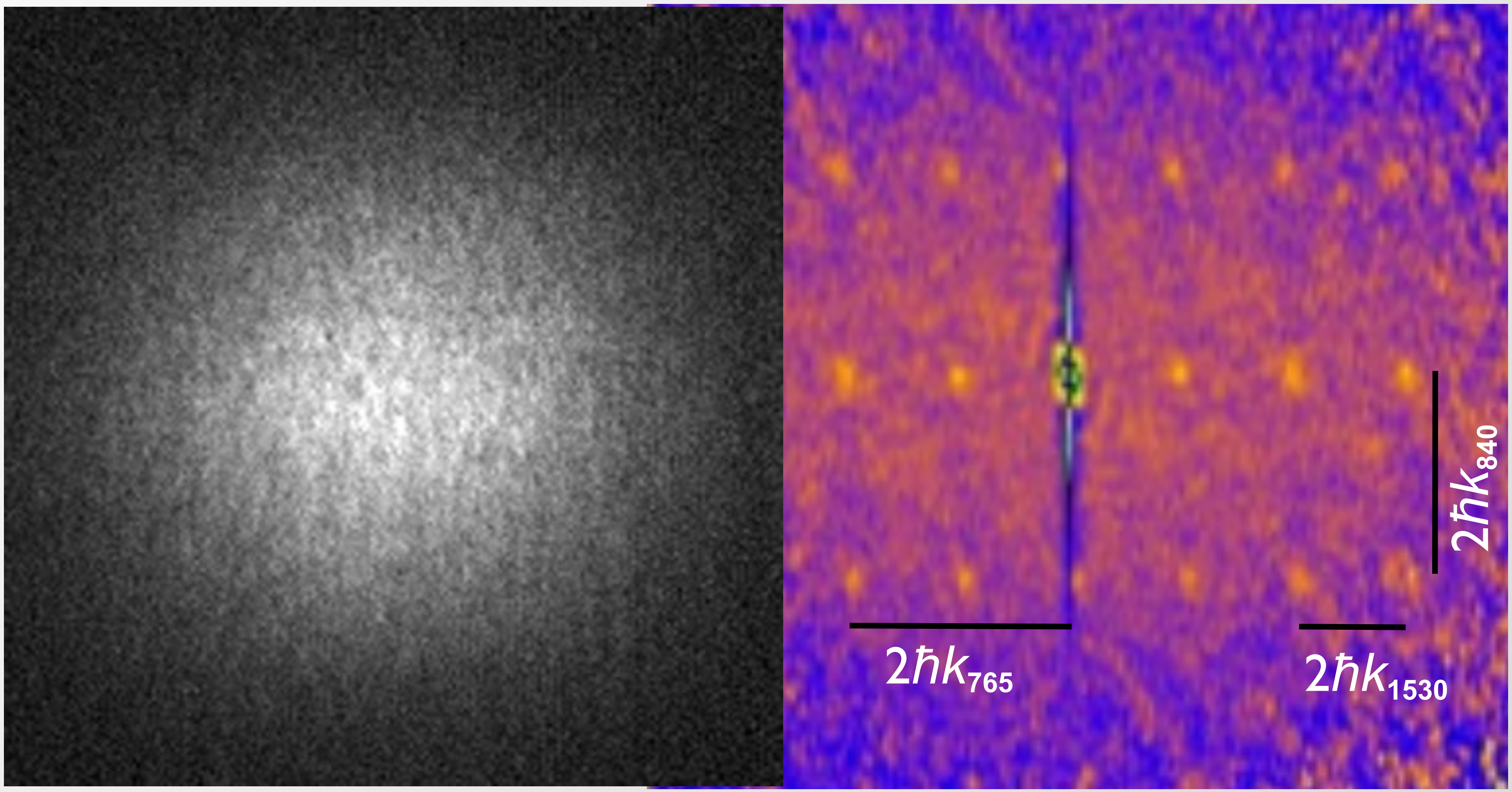
Mott State in long lattice

Increase short lattice

Switch off long lattice

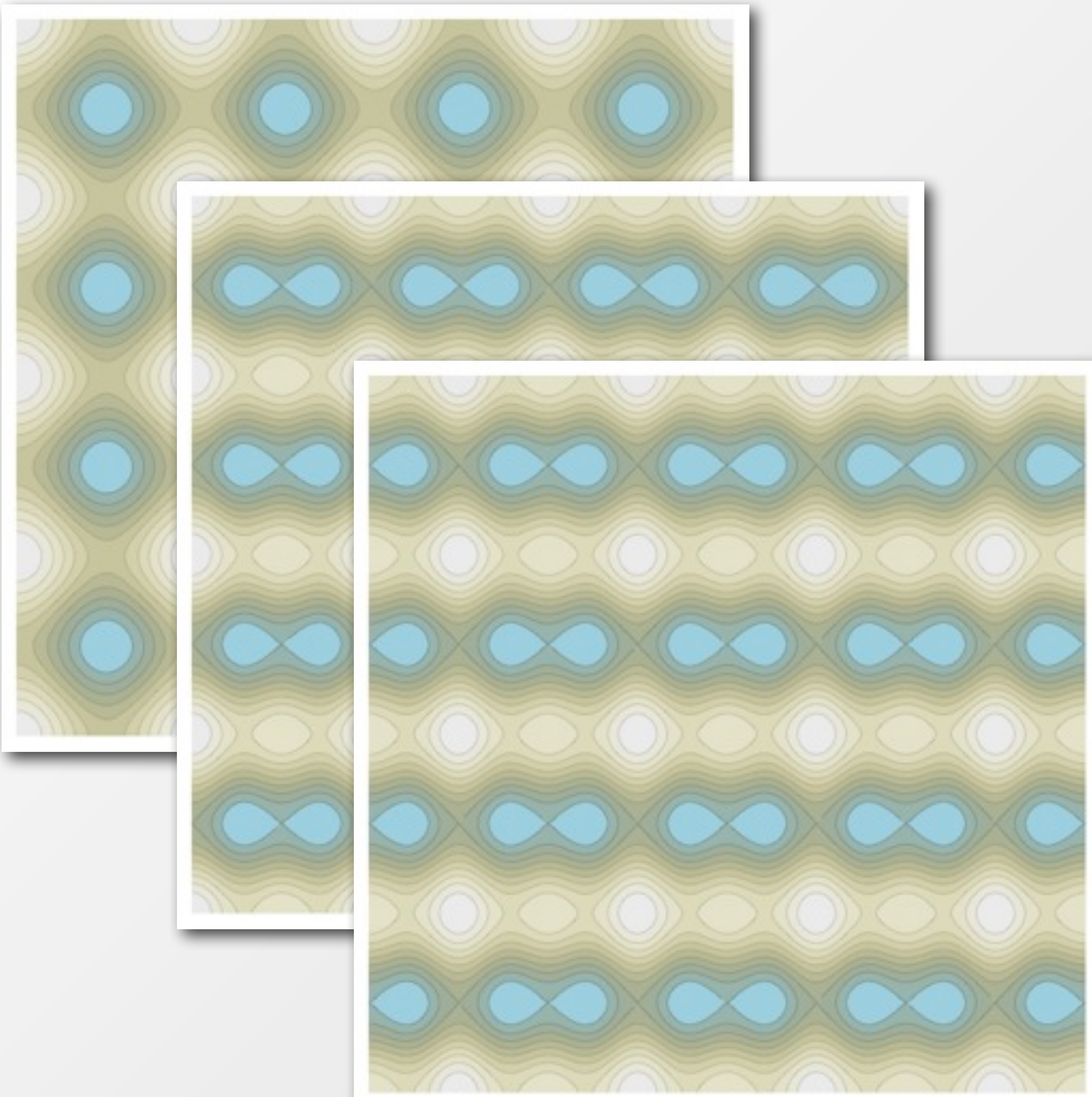
Release

Patterned correlations



Detection of density wave via noise correlations.

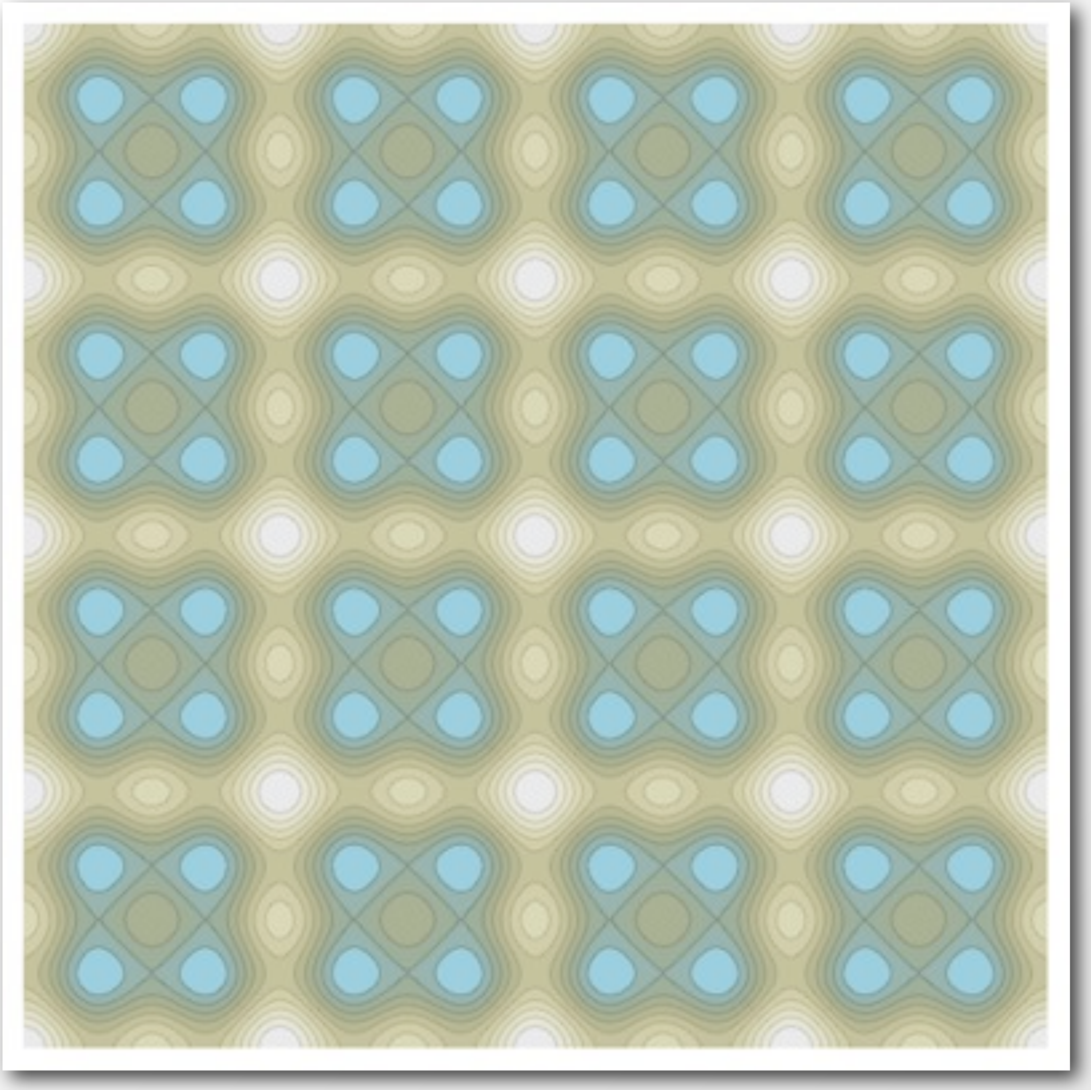
2D Superlattice Geometries (1 SL)



Controllable couplings and dynamics

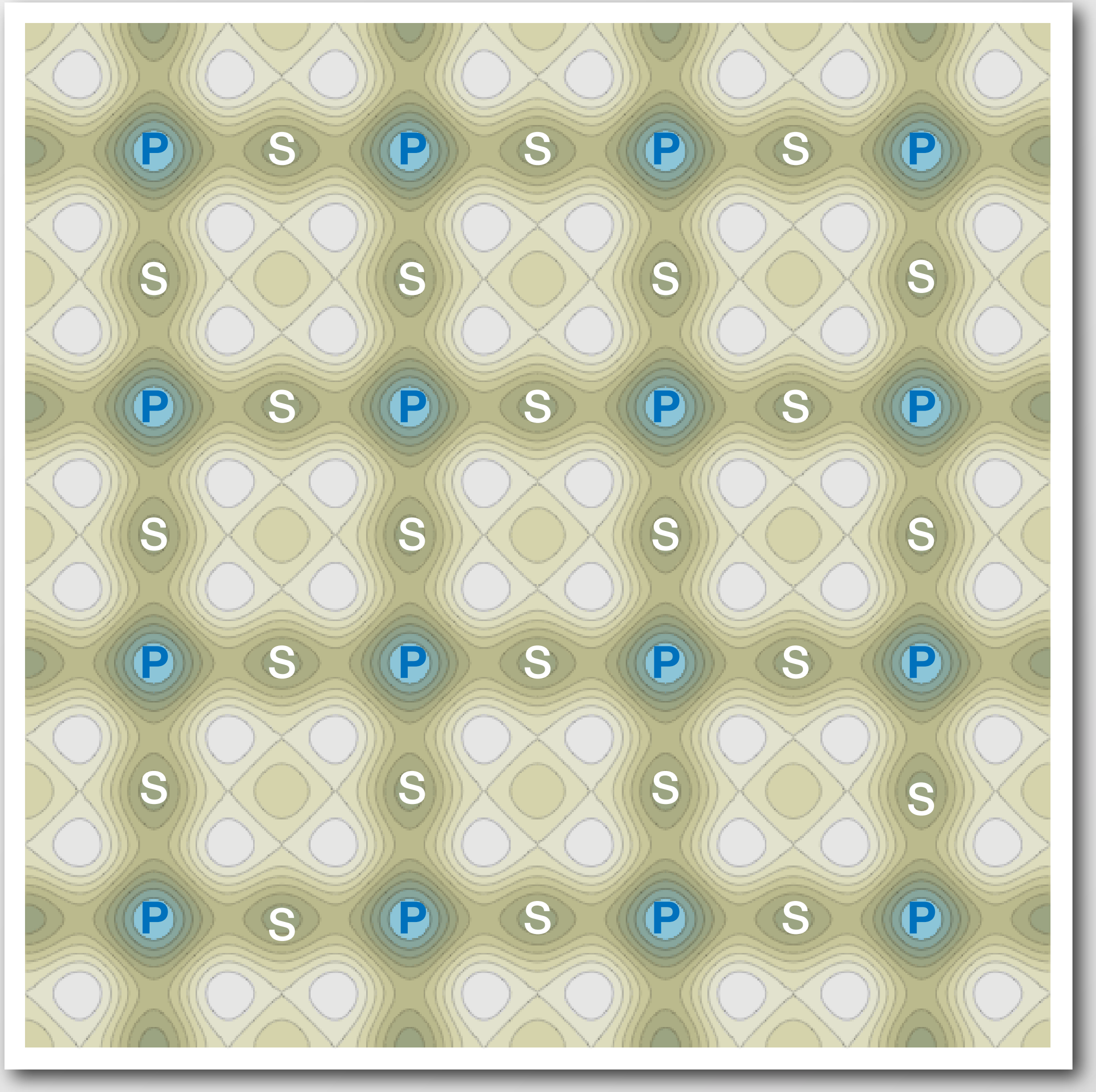
Superlattice useful for controlling and detecting spin correlations

2D Superlattice Geometries (2 SL)



Coupled Plaquette Systems

see B. Paredes & I. Bloch, PRA **77**, 23603 (2008)
S. Trebst et al., PRL **96**, 250402 (2006)



Higher Lattice Orbital Physics

see V. Liu, A. Ho, C. Wu and others work
exp: related to A. Hemmerich's exp.